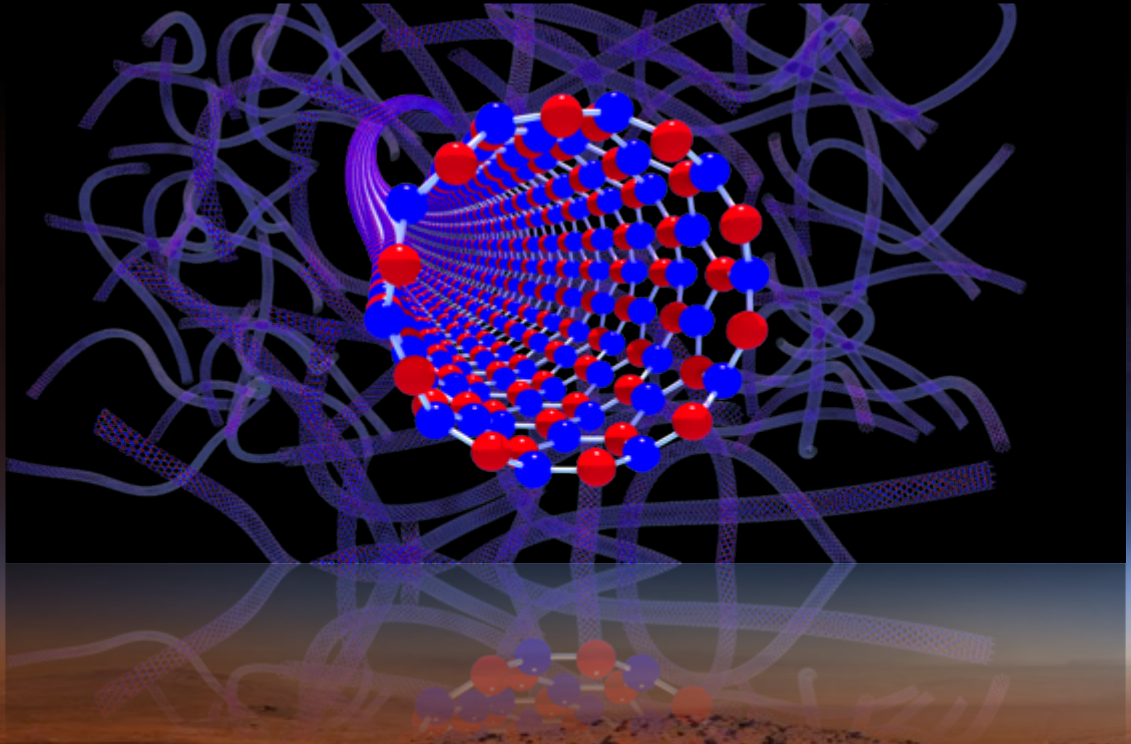
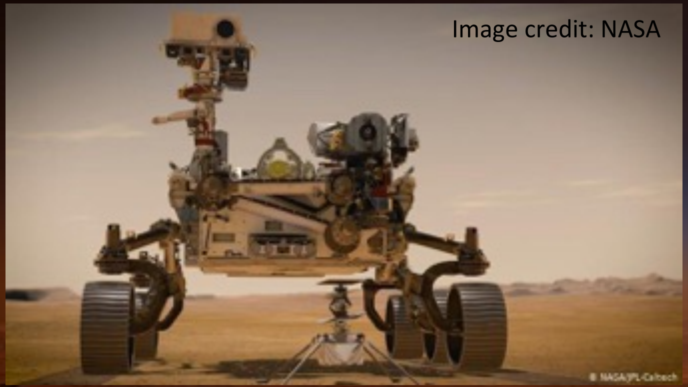
NASA Langley Research Center

Multifunctional Lightweight Structural Composites for Extreme Space Environments

Cheol Park, Sang-Hyon Chu*, and Catharine Fay





Advanced Materials and Processing Branch, NASA Langley Research Center, Hampton VA USA

Outline

- Motivation: Extreme Environments in Space
- Current NASA Space Projects: Artemis Program
- Introduction of Boron Nitride Nanotube (BNNT)
- BNNT and BNNT Composite Application
- Multifunctional Properties in Extreme Environments
  - Dispersion and Purification
  - Mechanical Properties
  - Thermal Properties
  - Sensor/Actuator/Energy Harvester
  - Radiation Shielding
- Summary

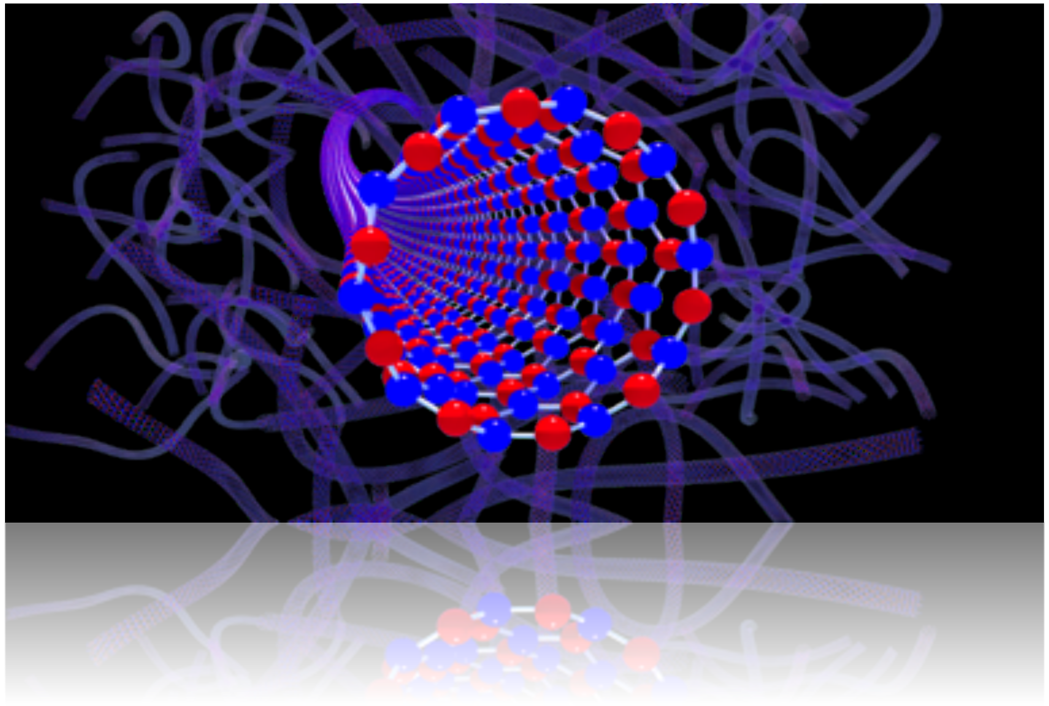
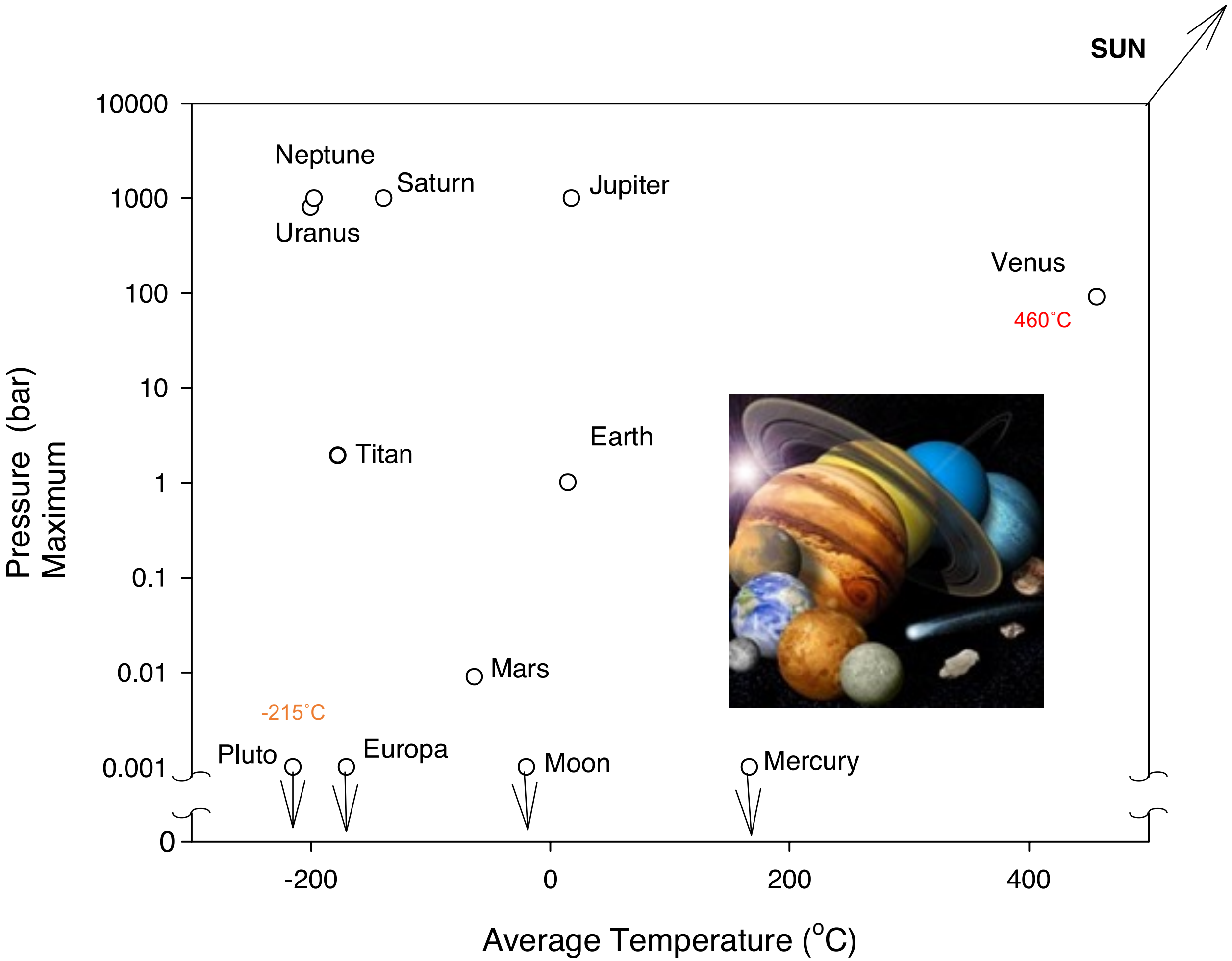


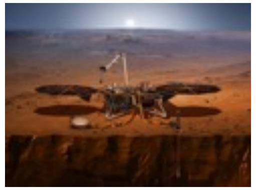
Image Credit: NASA

Extreme Environments in Space Exploration



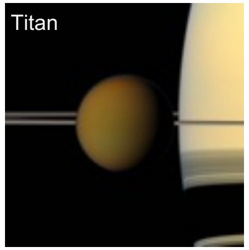
http://www.jpl.nasa.gov/solar_system/
17NASA Extreme Environments Tech Space missions Report FINAL

Lunar surface
-173 to 127˚C
-247˚C (25K) at pole
Sharp abrasive edge dust
Radiation
1/6 Earth gravity



Mars surface
-126 to 21˚C
Sand storm
Radiation
Entry, Descent, & Landing

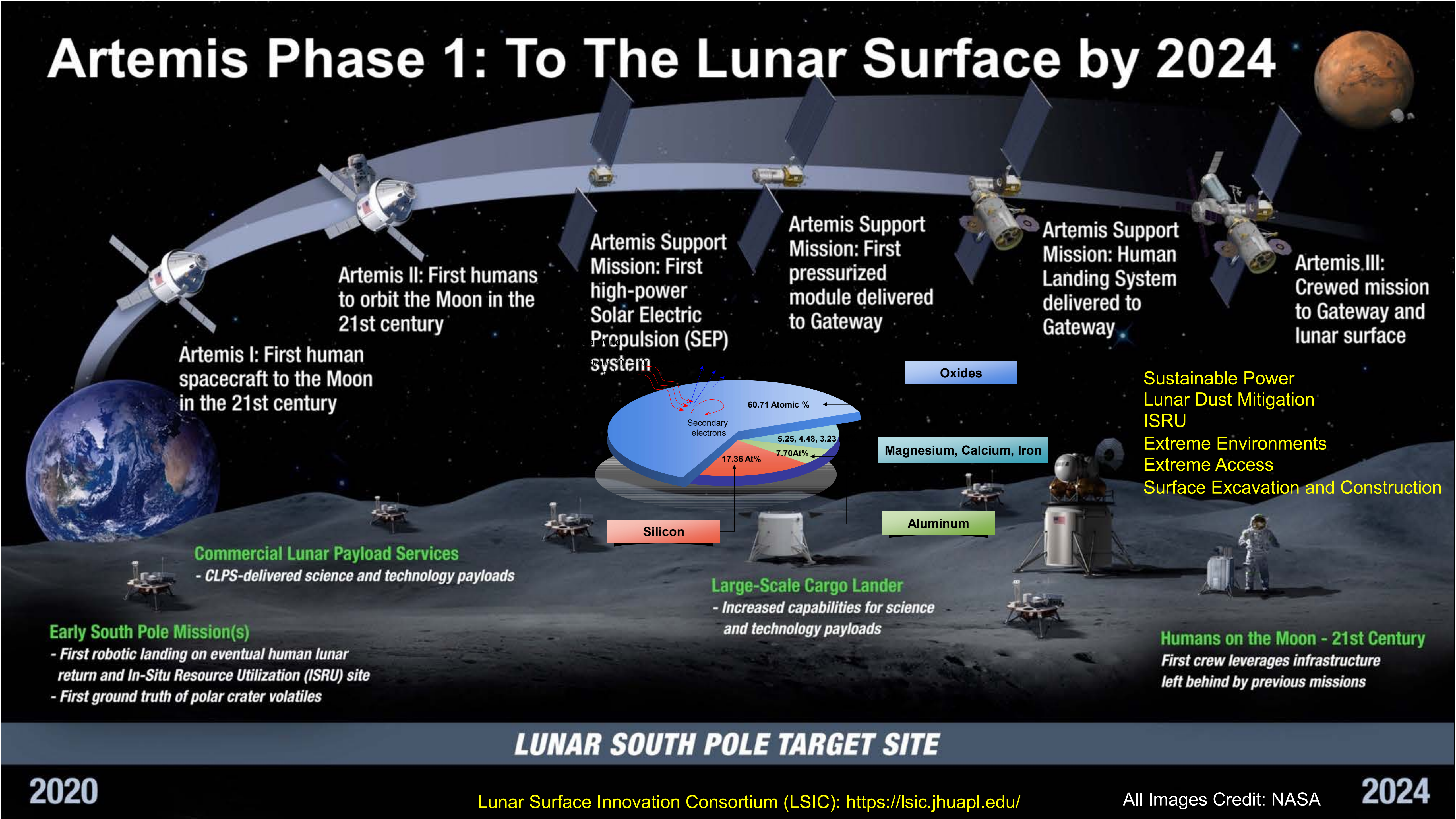
Deep space
2.7K
Radiation
Microgravity



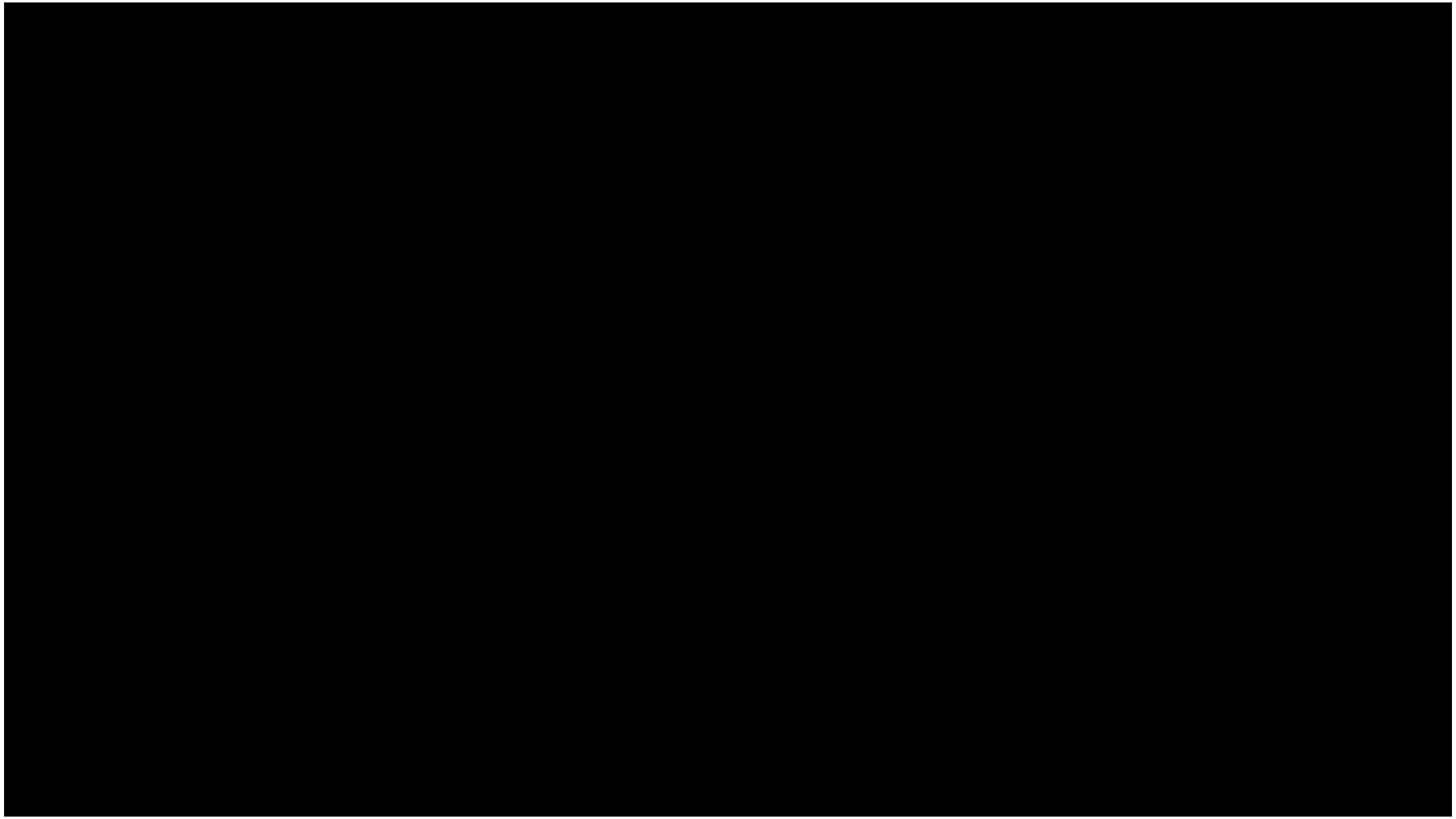
Hypersonic heat flux at atmospheric entry: Heat fluxes often exceeding 1 kW/cm^2
Hypervelocity impact: Higher than 20 km/sec
Extreme temperatures: Lower than −240˚C and Exceeding +460˚C
Thermal cycling: Cycling between temperature extremes outside of the military standard range of −55˚C to +125˚C
High pressures: Exceeding 20 bars
High radiation: Total ionizing dose (TID) exceeding 300 krad (Si), GCR, SPE, Neutron
Low and High gravity: microgravity on comets, 2.5g on Jupiter, launch, entry, descent

Artemis Program: Send 1st woman & next man to the Moon by 2024 (about $40B), and then Mars and Beyond

All Images Credit: NASA


Artemis Phase 1: To The Lunar Surface by 2024
Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission: Human Landing System delivered to Gateway
Artemis III: Crewed mission to Gateway and lunar surface
Oxides
60.71 Atomic %
Secondary electrons
5.25, 4.48, 3.23
7.70At%
17.36 At%
Magnesium, Calcium, Iron
Silicon
Aluminum
Sustainable Power
Lunar Dust Mitigation
ISRU
Extreme Environments
Extreme Access
Surface Excavation and Construction
Commercial Lunar Payload Services
- CLPS-delivered science and technology payloads
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
- First ground truth of polar crater volatiles
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2020
Lunar Surface Innovation Consortium (LSIC): https://lsic.jhuapl.edu/
All Images Credit: NASA
2024

ISRU Landing Pad: Multipurpose Cassegrain System

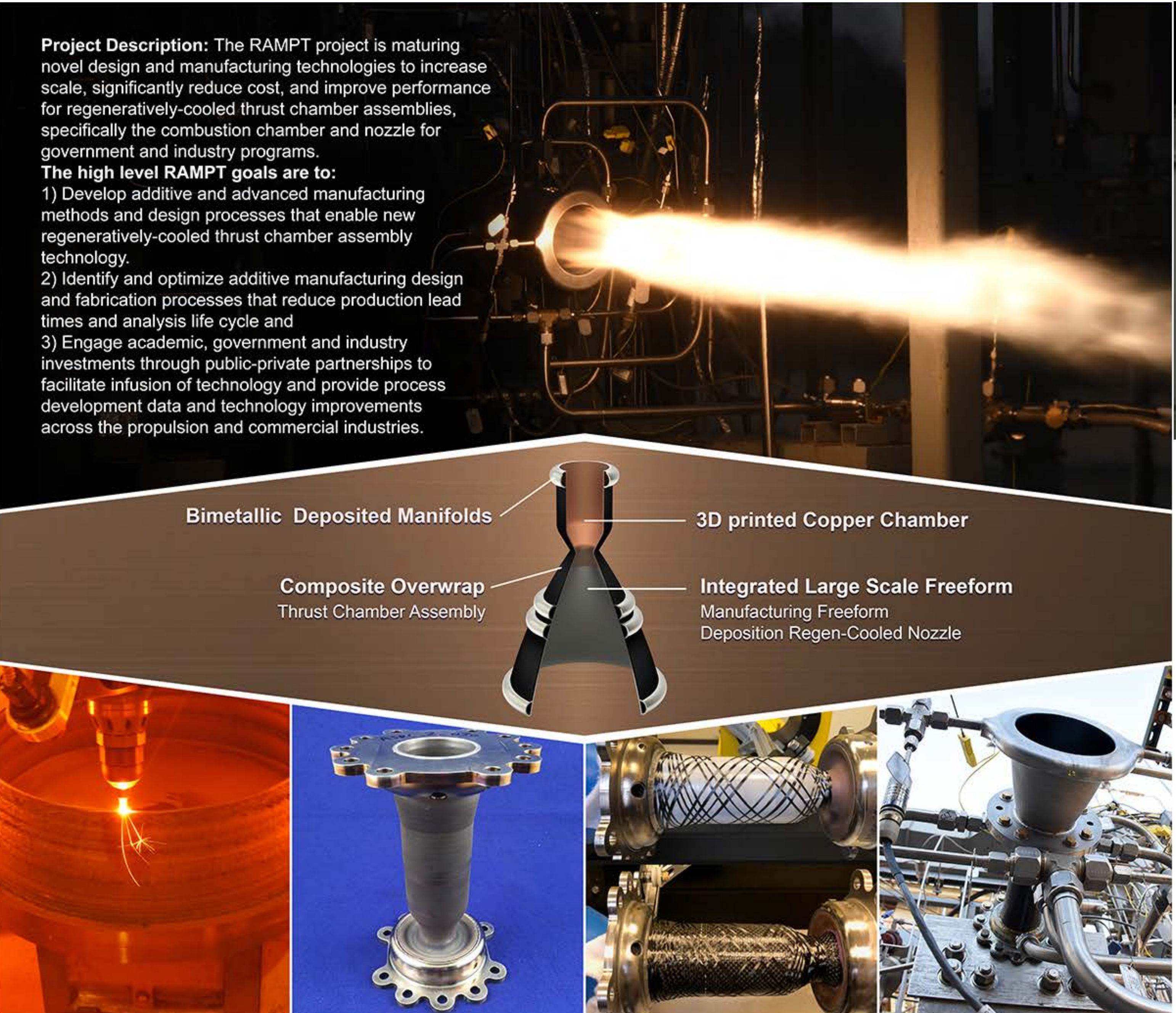


https://www.youtube.com/watch?v=mpXdY2v5FDI&feature=youtu.be

Credit: Bob Moses and Sang H Choi (NASA LaRC)

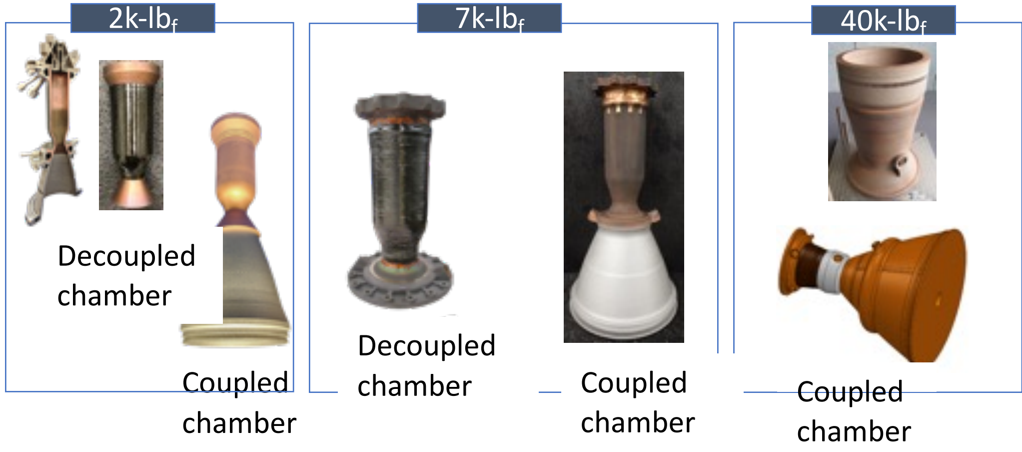
Video Credit: NASA

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)



Large-Scale 3D Printing for Rocket Engines

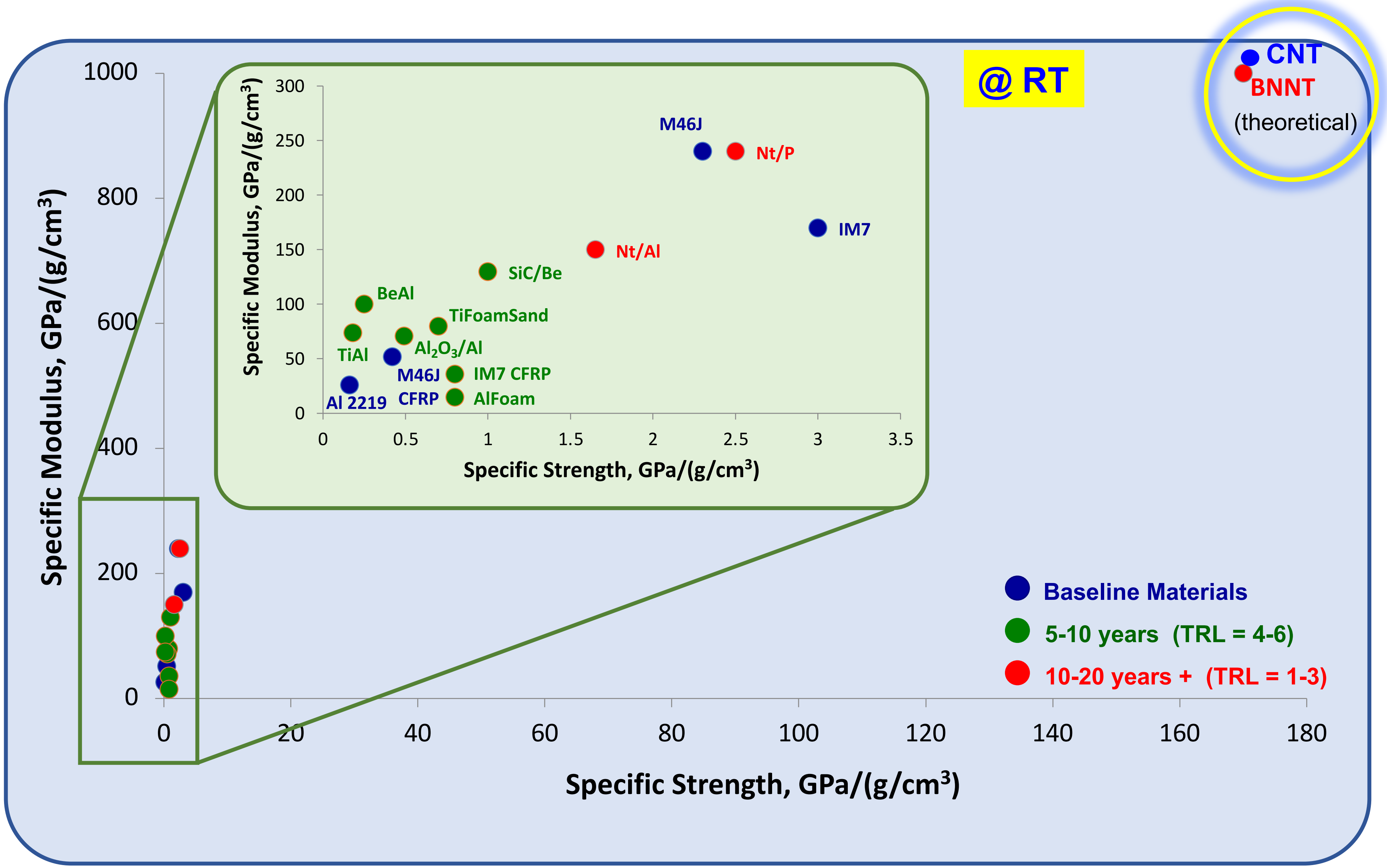
https://www.youtube.com/watch?v=_JHqdVU9Ebo&t=3s



CAMX, Dallas, TX (2021)

All Images Video Credit: NASA

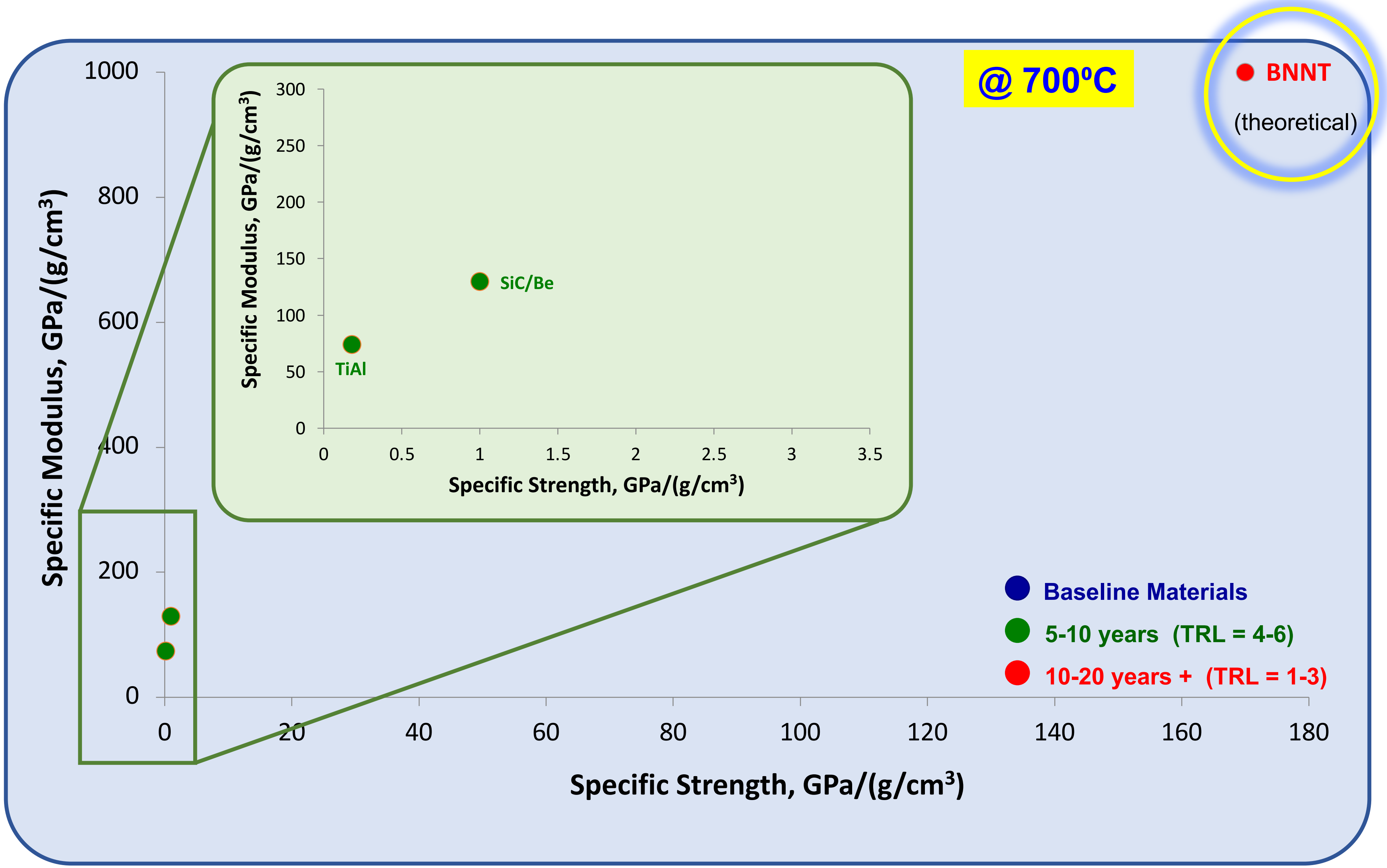
Motivation: Properties of Materials for Vehicle Structure



Charlie E. Harris, M. J. Shuart, H. Gray, NASA/TM-2002-211664

Nanotube values are theoretical.

Motivation: Properties of Materials for Vehicle Structure



Charlie E. Harris, M. J. Shuart, H. Gray, NASA/TM-2002-211664

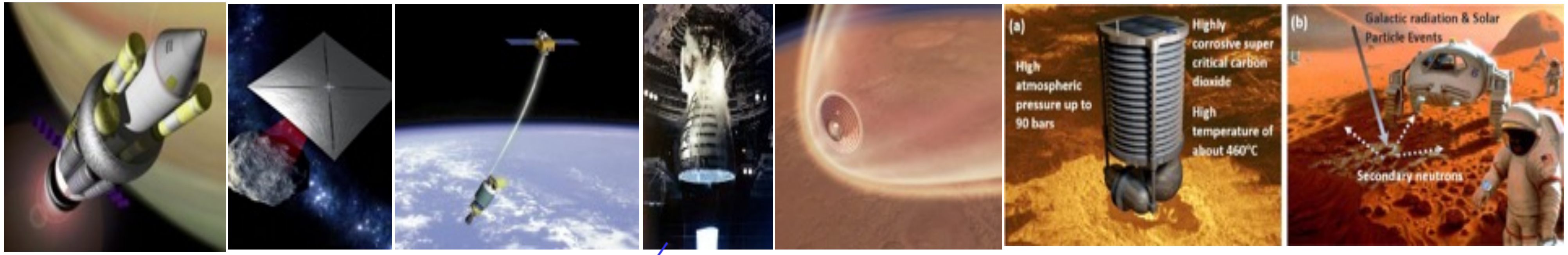
Nanotube values are theoretical.

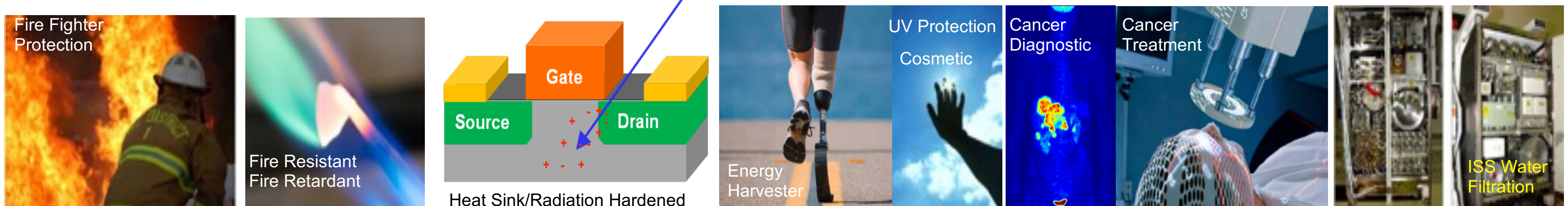
Nanotube Comparison (Theoretical)

	Carbon Nanotubes	Boron Nitride Nanotubes
Electric Properties	Metallic or semiconducting	Wide band gap (about 6.0 eV) Insulation, corrosion resistant
Mechanical Properties (Young's Modulus)	1.33 TPa (very stiff)	1.18 TPa (very stiff)
Thermal Conductivity	>3000 W/mK (highly conductive)	~300–3000 W/mK (highly conductive)
Thermal Oxidation Resistance	Stable up to 300-400 ˚C in air	Stable to over 900 ˚C in air
Neutron Absorption Cross-Section	C = 0.0035 barn	B = 767 barn (B^{10} ~3800 barn) N = 1.9 barn Excellent radiation shielding
Polarity	No dipole	Permanent dipole Piezoelectric (0.25-0.4 C/m^2)
Surface Morphology	Smooth	Corrugated Better interfacial strength for composites, ionic bonding
Color	Black	White (can be colored)
Coefficient of Thermal Expansion	-1 x10^{-6} K^{-1} (very low)	-1 x 10^{-6} K^{-1} (very low)

Significance of the BNNT Innovation

- **Structural/Mechanical**: **lightweight** composite armor, thermal protection, engine components, and radiation shielding materials for **extreme environments**.
- **High stiffness as well as high toughness** for spacecraft and space suits, ultrastrong tethers, meteorite impact protection layers, protective gear for astronauts.
- **Space lubricants** without moisture.
- **High temperature** thermal protection systems (**TPS**) used in the **nose cap**, wing **leading edges**, **engine parts**, lubricants, and planetary **Entry, Descent, & Landing** (**EDL)** TPS.
- **Fire resistant and retardant.**
- **High temperature sensor, actuator, energy harvesting devices** in extreme environments.
- **Radiation shielding, UV (ultraviolet) protection,** and electromagnetic transparency while decreasing aircraft weight.
- **Radar transparency** mitigates Electromagnetic Interference (EMI) and Radio Frequency (RF) blackout.
- **Efficient zero-energy water filter and desalination membrane in microgravity**.



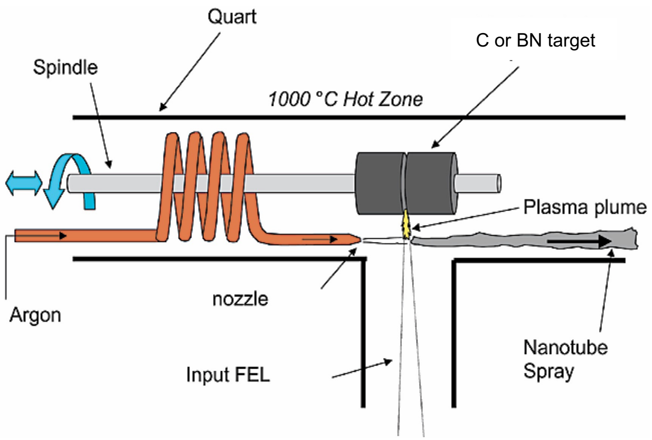


All Images Credit: NASA

BNNT Synthesis

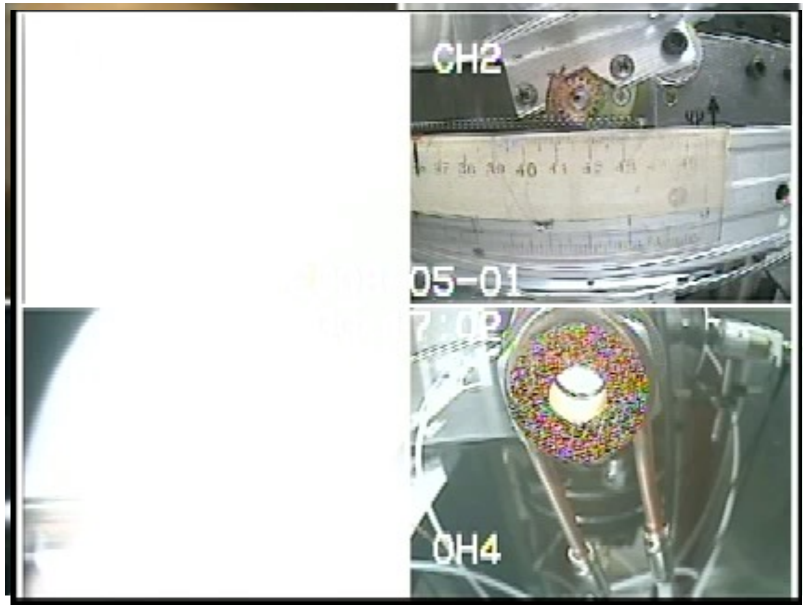
High Temperature-Pressure (HTP) BNNT

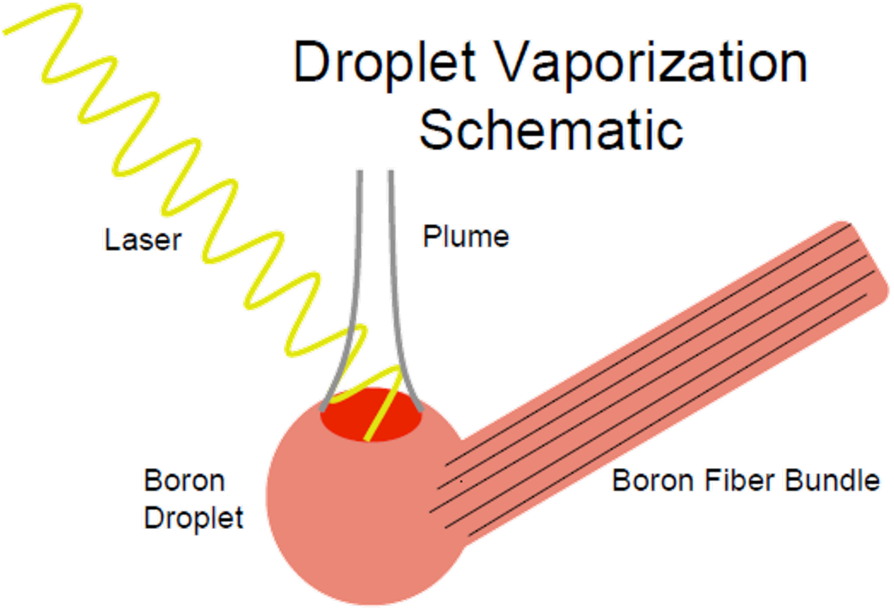
- Free Electron Laser (FEL) or CO_2 laser
- ***No Catalyst, only B and N resource***
- Very long, small diameter, highly crystalline BNNT



Nanotechnology, **20** 505604 (2009)
US Patent 8206674 B2 (2012)

BNNT Synthesis Lab: NASA Langley (1st Gen)





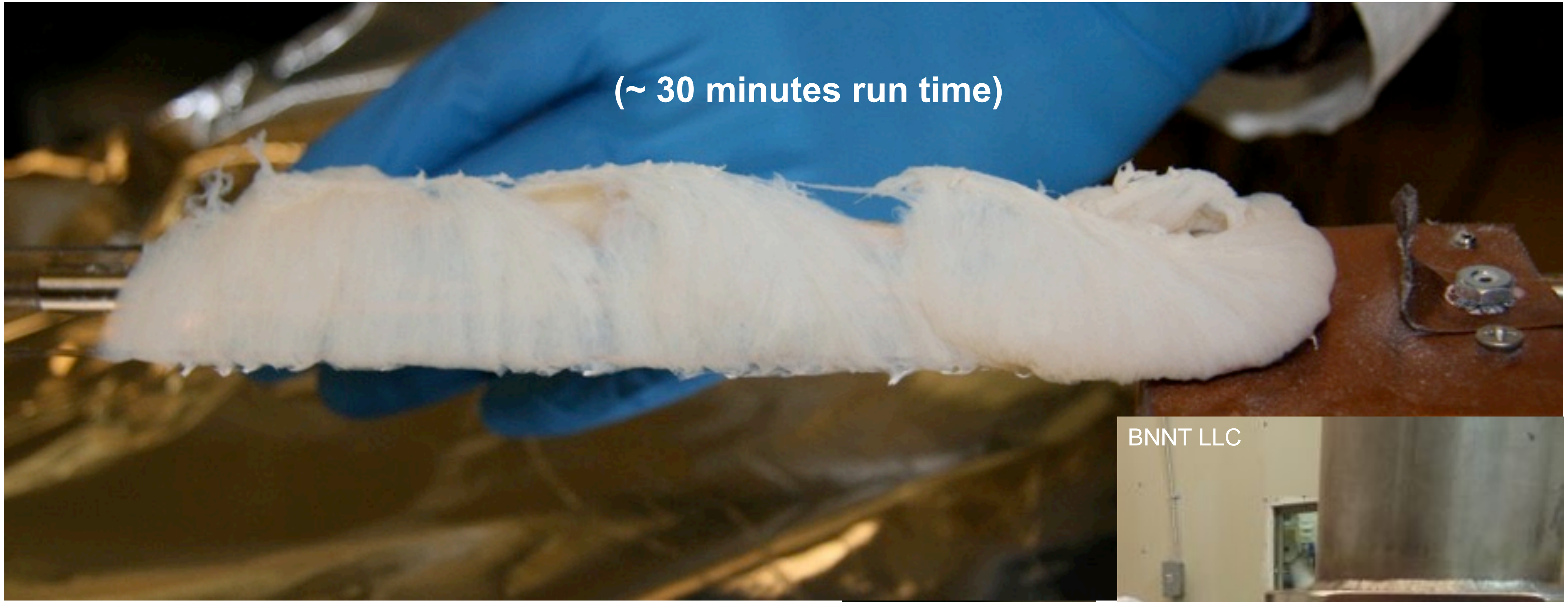
High Temperature Pressure (HTP) BNNT

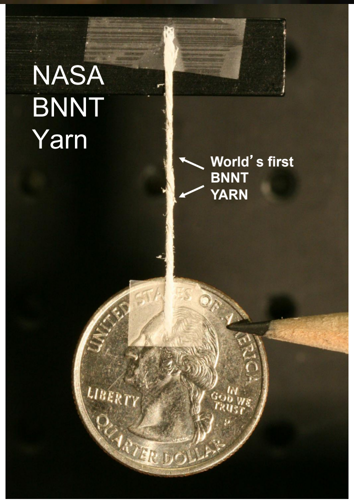
- 5 kW of infrared radiation @ 10.6μm
- Heat source for vaporizing Boron feed stock above 3500ºC
- Pressurized with Nitrogen to 13.6 atm (200 psi)

Nanotechnology, **20** 505604 (2009)
J. Thermophysics and Heat Transfer **27** 369 (2013)
Proc. SPIE **9060** 906006 (2014)

All images credit: NASA

Cotton-like High Pressure and Temperature (HTP)-BNNT





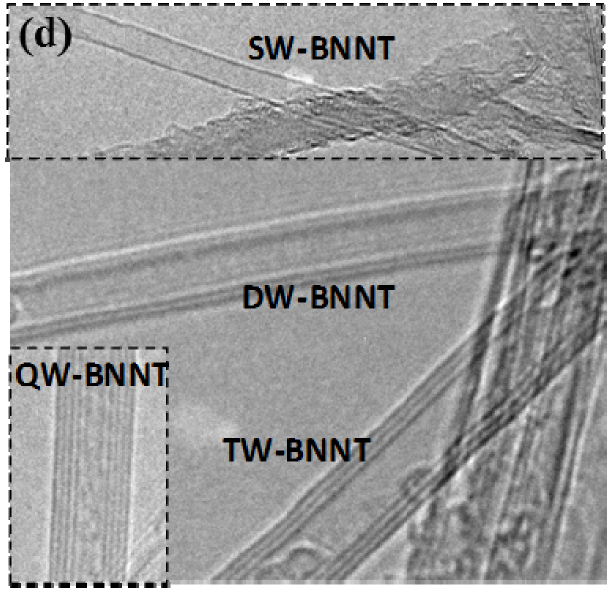
(From: M. W. Smith et al, Nanotechnology, 20, 505604 (2009))

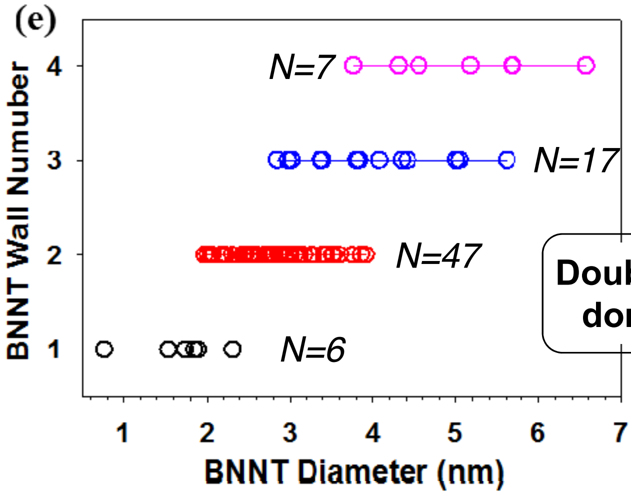
Benefits

- One-to-few-walled tubes with high crystallinity
- Very long, high-aspect ratio tubes
- High scale-up potential
- No toxic catalysts (only B and N as reactants)
- Standard industrial cutting/welding lasers
- High service temperature (over 800ºC)
- Highly electroactive (due to the B-N polar bond)
- Neutron radiation shielding (due to their B content)

Nanotube Wall Number and Distribution of HTP-BNNTs

TEM Micrographs

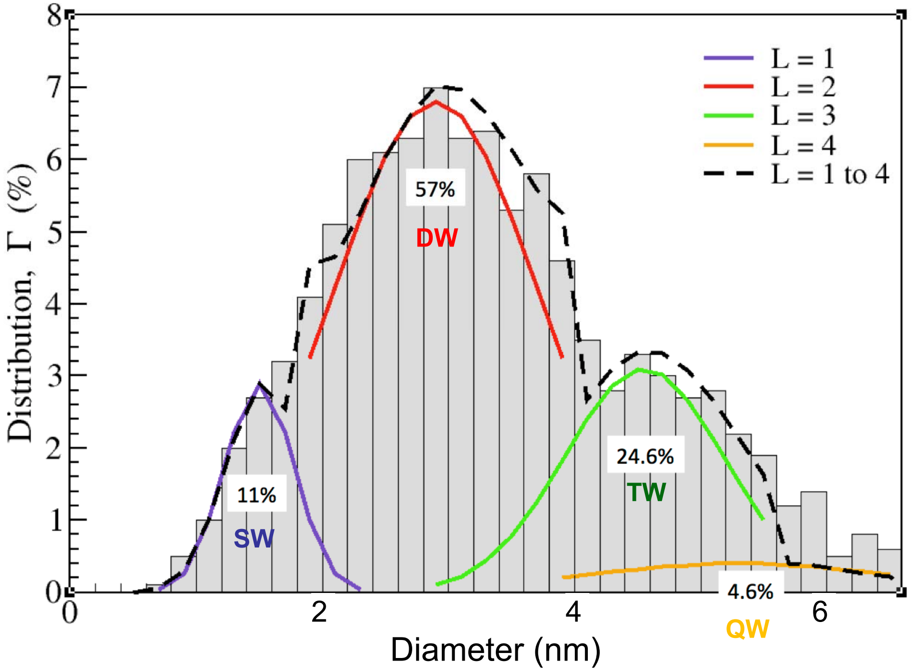




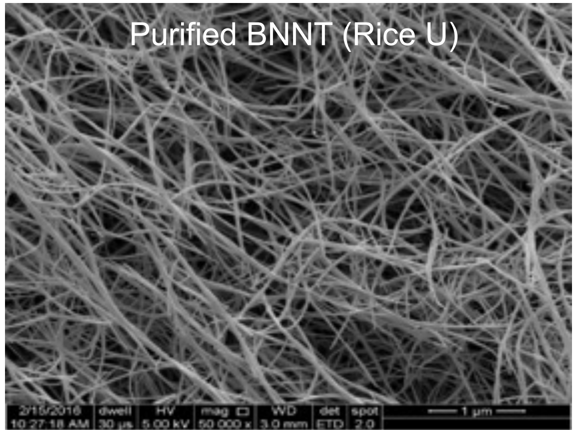
Double-walled dominance

Nanotechnology, **23** 095703 (2012)

Based on AFM measurements of 1,000 randomly selected individual BNNTs

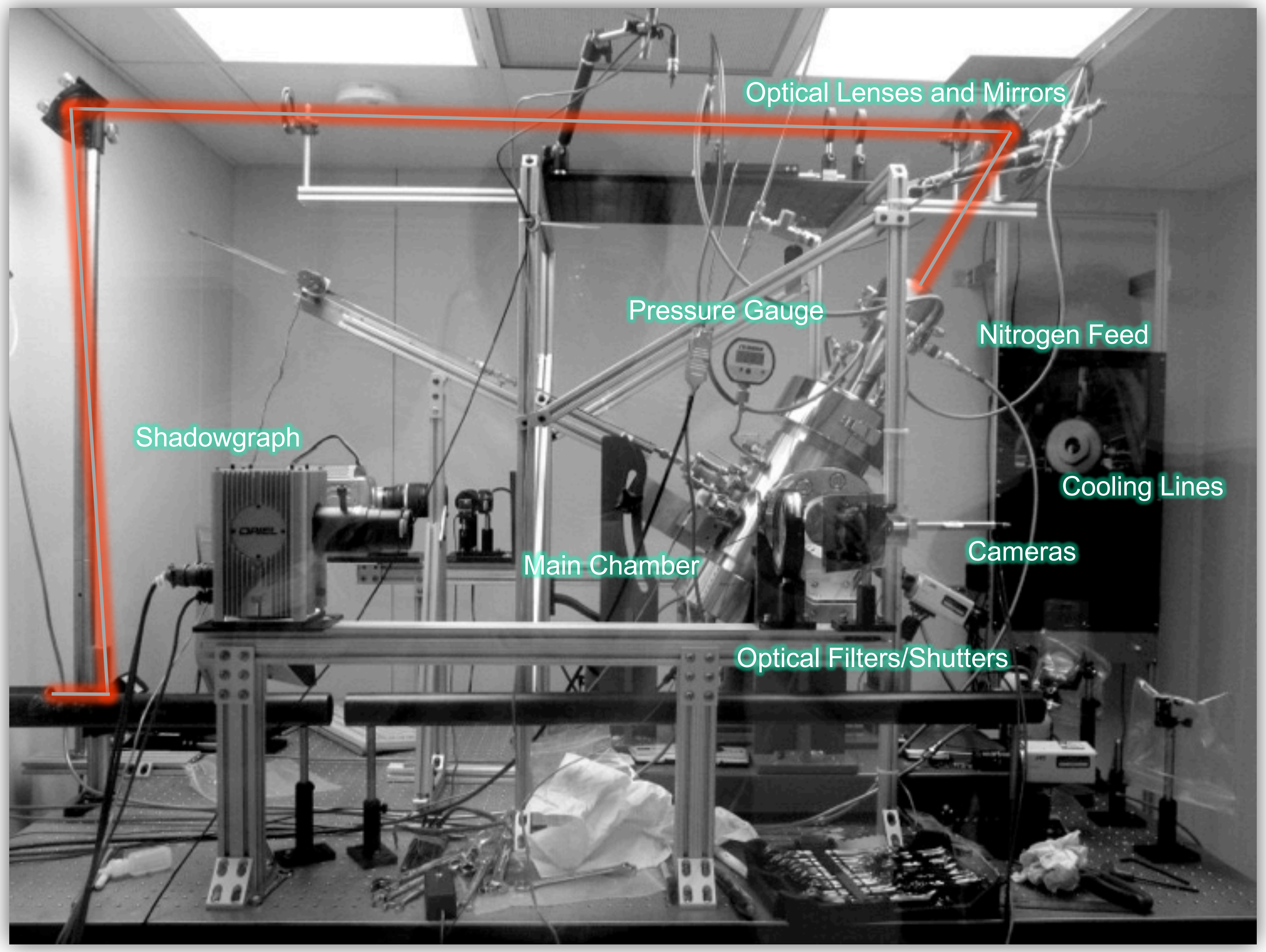


SW: 11%
DW: 57%
TW: 24.6%
QW: 4.6%
Total: 97.2%



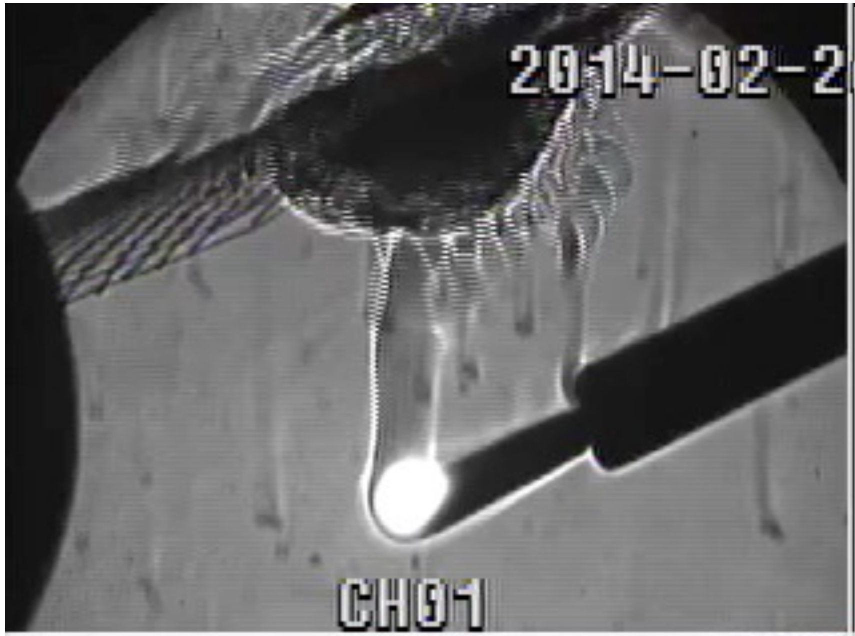
Comp. Mater. Sci., **135** 29 (2017)

National Institute of Aerospace (NIA) BNNT Science Chamber

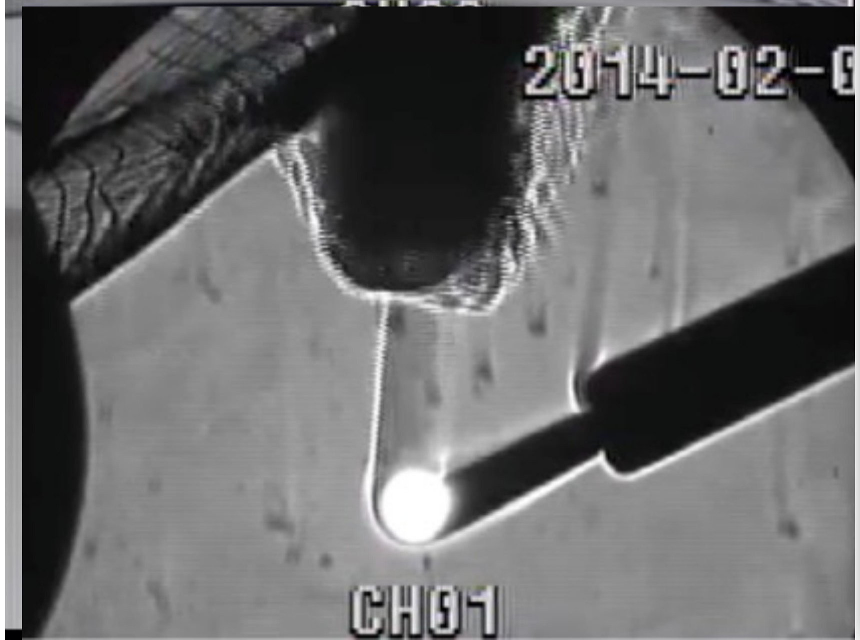


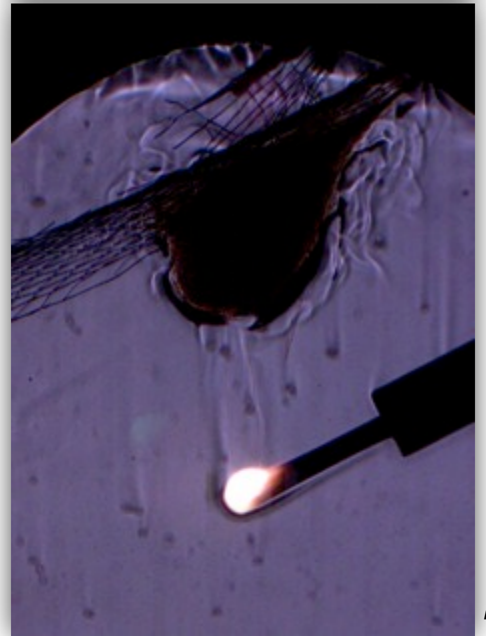
All images credit: NASA/NIA

NIA Science Rig HTP BNNT Run (Snapshots)



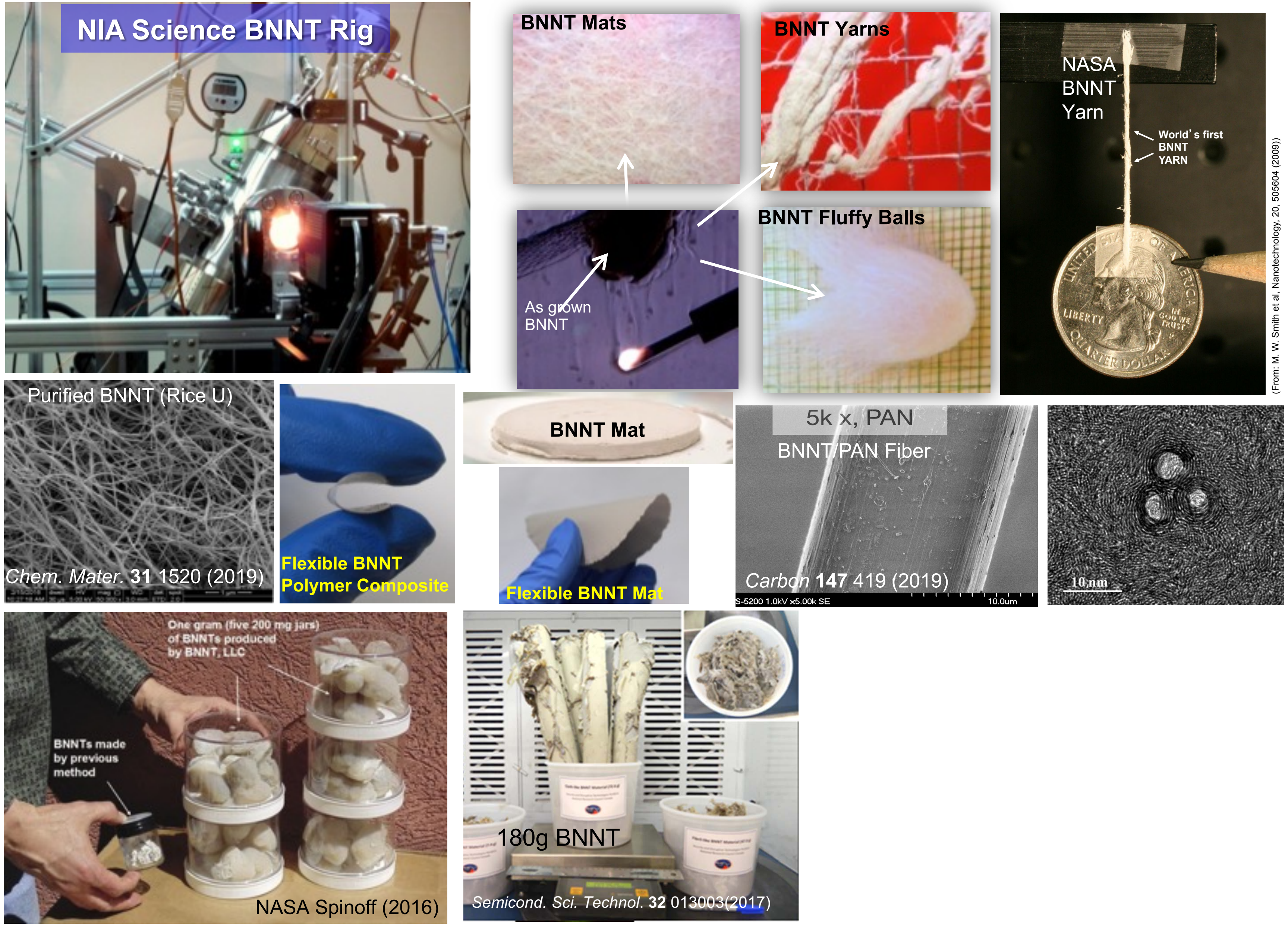
All images credit: NASA/NIA





Proc. SPIE **9060** 906006 (2014)

BNNT Scale-Up and Various Forms of BNNT



All images credit: NASA

Dispersion and Purification

Thermodynamic Approach: Effective BNNT Dispersion

Essential for Quality Yarn, Fabric, and Composite Formation

Thermodynamic Approach:
Gibbs Free Energy of Mixing

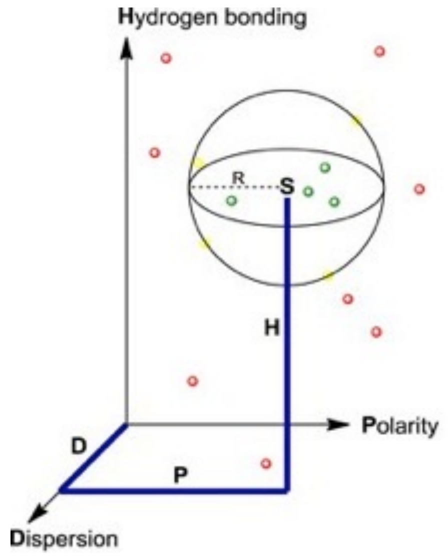
$$\Delta G_{mix} = \Delta H_{mix} - T^{*}\Delta S_{mix}$$

If ΔG_{mix} is negative, spontaneous mixing happens to form a homogeneous solution

Hansen Solubility Parameters (HSP)
(d_d, d_p, d_h): “like dissolves like”

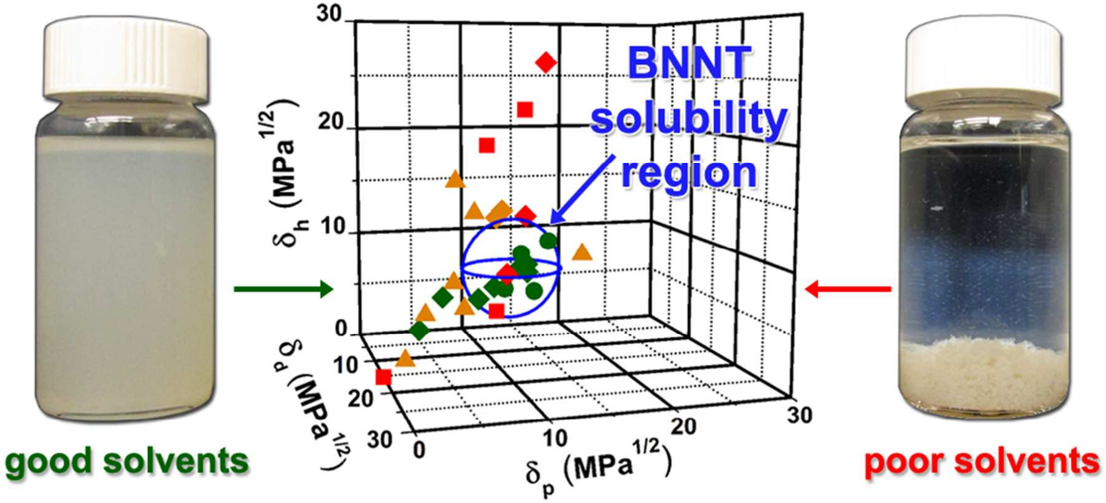
$$\delta_t^2 = \delta_d^2 + \delta_p^2 + \delta_h^2$$

d_t^2: Hildebrand parameter
d_d: dispersion component
d_p: polar component
d_h: hydrogen bonding component



Example of 3D Hansen space*

Single and Co-solvents



BNNT Hansen Solubility Parameters
δ_d, δ_p, δ_h = 16.8, 10.7, 9.0 MPa$^{1/2}$
δ_t = 21.8 MPa$^{1/2}$

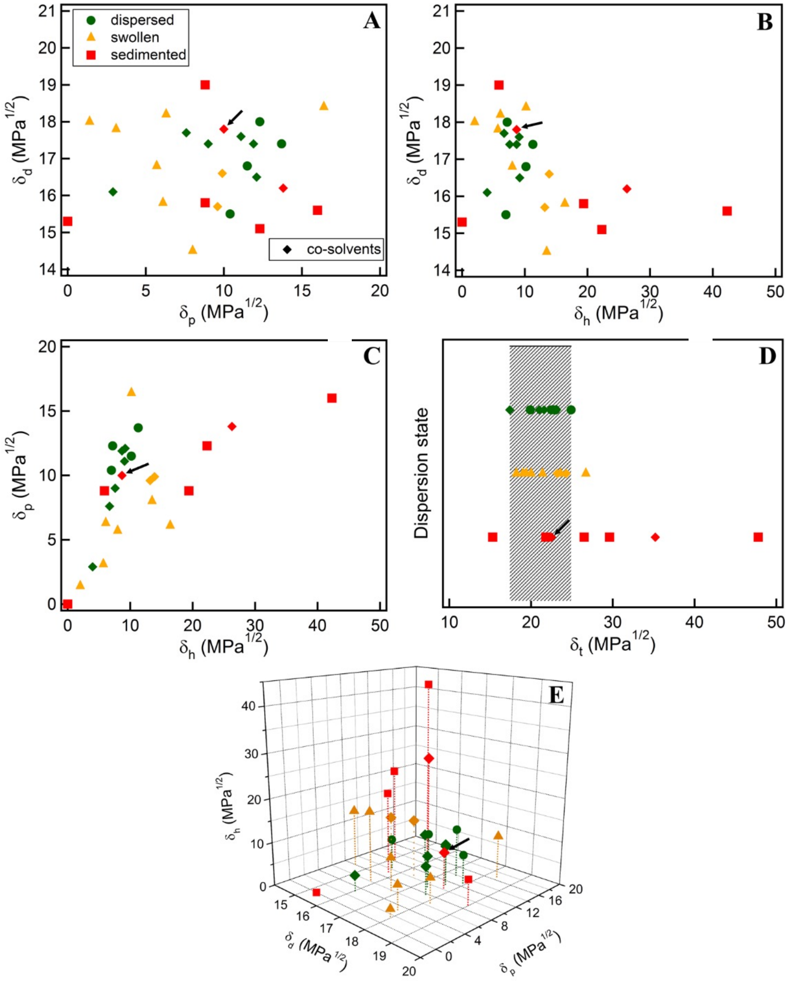
In-situ polymerization with BNNT under shear and sonication

Nanoscale **8** 4348 (2016)

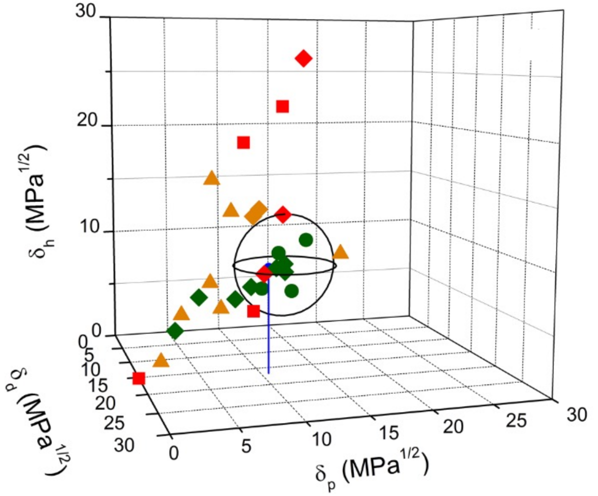
*http://confidentsolventselection.com/about/solubility-parameters.html

Dispersion: Dispersion State of Single and Co-solvents

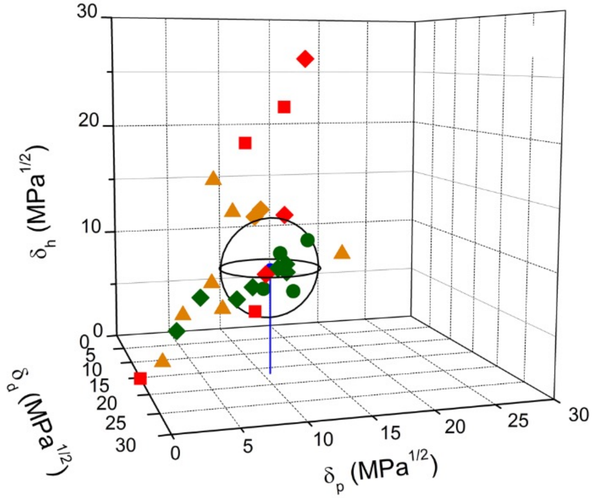
Co-solvent	δ_d, MPa$^{1/2}$	δ_p, MPa$^{1/2}$	δ_h, MPa$^{1/2}$	δ_t, MPa$^{1/2}$	Dispersion state (stirring only)	Dispersion state (stirring + 30 mins sonication)	R_a[c]	*RED*[d]
THF-NMP	17.4	9.0	7.6	21.0	swollen	dispersed/swollen[b]	2.51	0.58
DMF-acetone	16.5	12.1	9.2	22.4	swollen[a]	dispersed/swollen[b]	1.54	0.36
DMAc-NMP	17.4	11.9	8.7	22.8	swollen[a]	dispersed/swollen	1.72	0.40
DMSO-THF	17.6	11.1	9.1	23.1	swollen	dispersed/swollen[b]	1.65	0.38
DMF-toluene	17.7	7.6	6.7	21.6	swollen	dispersed	4.26	0.99
IPA-DMF	16.6	9.9	13.9	24.3	sediment	dispersed/swollen[b]	4.98	1.16
ethanol-acetone	15.7	9.6	13.2	23.2	swollen	dispersed/swollen[b]	4.87	1.13
DMF-DCM	17.8	10.0	8.7	22.5	swollen	dispersed/swollen[b]	2.14	0.50
THF-hexane	16.1	2.9	4.0	17.4	sediment	dispersed/swollen	9.37	2.18
DMAc-water	16.2	13.8	26.3	35.2	swollen	sediment	17.62	4.10



Single Solvent Sphere



Co-solvent Sphere

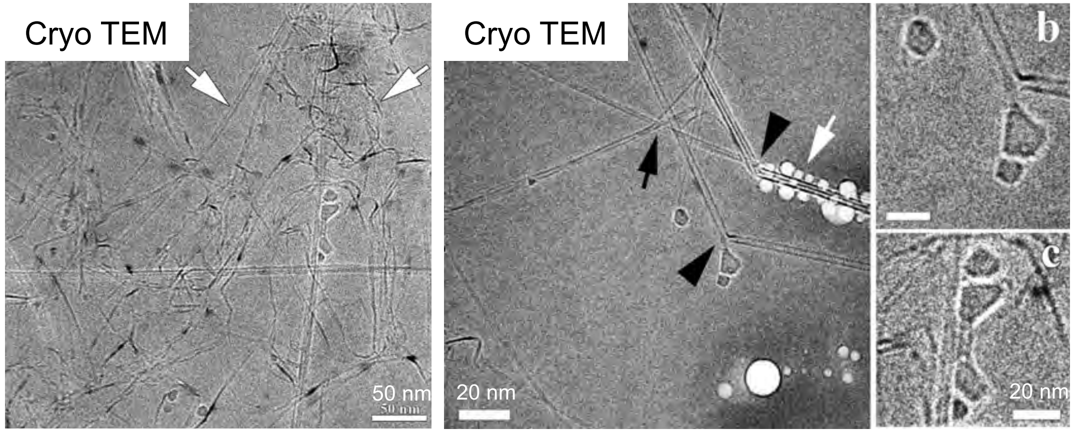


BNNT HSP
δ_d, δ_p, δ_h = 16.8, 10.7, 9.0 MPa$^{1/2}$
δ_t = 21.8 MPa$^{1/2}$

Nanoscale **8** 4348 (2016)

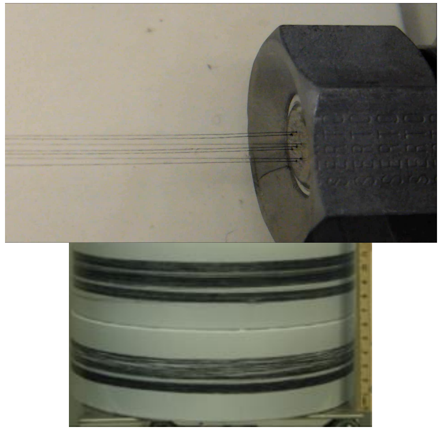
Dispersion and Purification

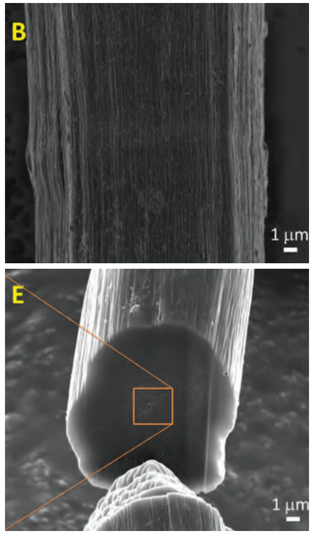
Dispersion in a Superacid (Chlorosulfuric acid)



BNNT in Chlorosulfuric acid (HSO_3Cl)

Continuous CNT Spinning



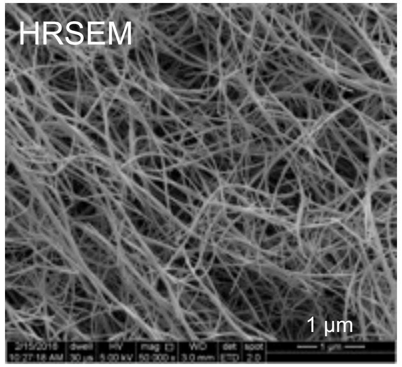


Rice U Nanotube Spinning (*Science* **339** 182 (2013))

Purification: Wet Thermal Oxidation

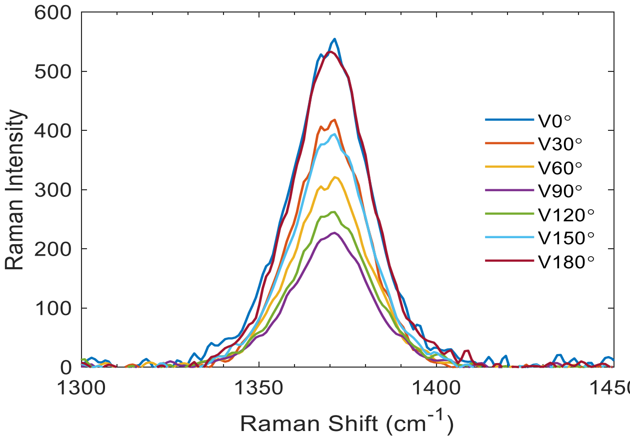
As grown BNNT

Purified BNNT



Purified BNNT

Raman: Degree of Alignment



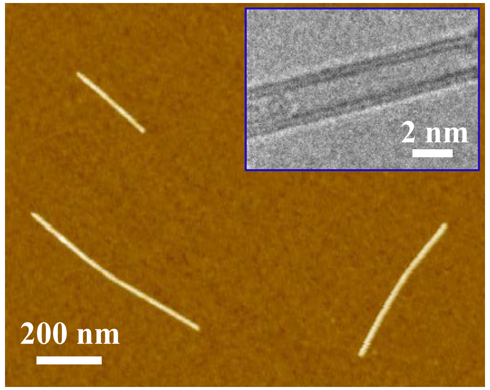
Credit: Prof Pasquali Group at Rice University

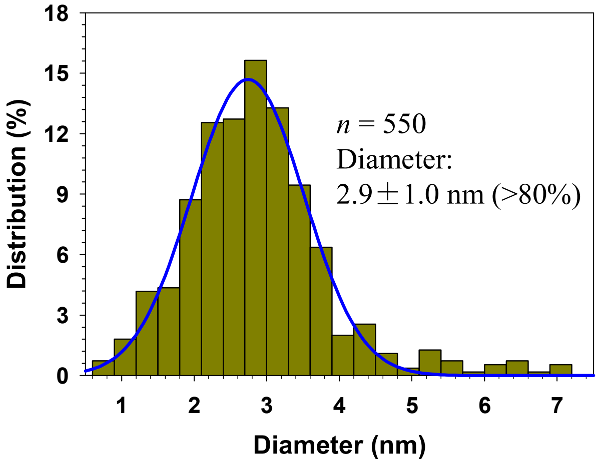
Langmuir **33** 14340 (2017), *Nano Lett* **18** 1615 (2018), *Chem. Mater.* **31** 1520 (2019)

Mechanical and Thermal Properties

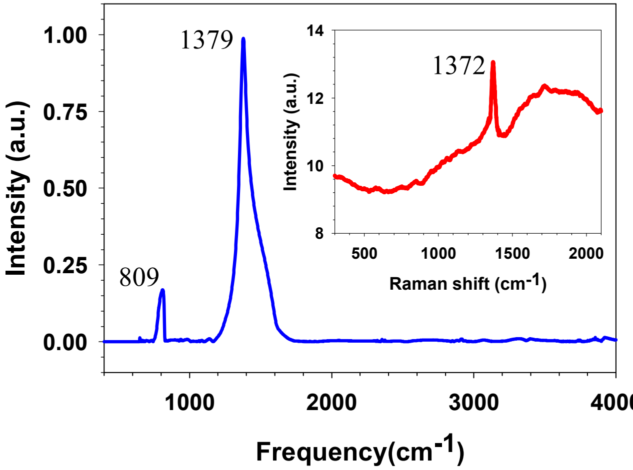
In-situ Single BNNT Test inside of an SEM

AFM

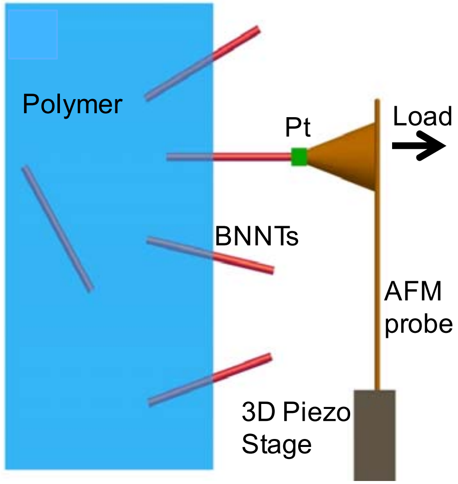




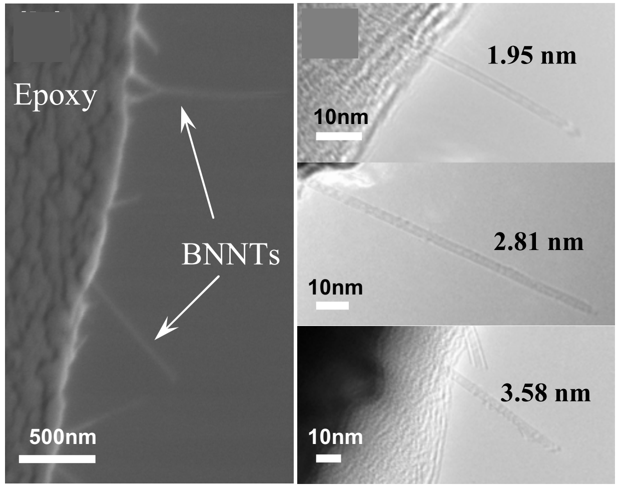
FTIR and Raman



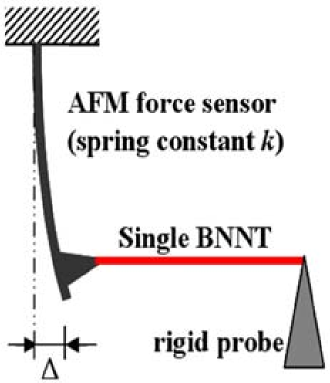
Pull-Out Test

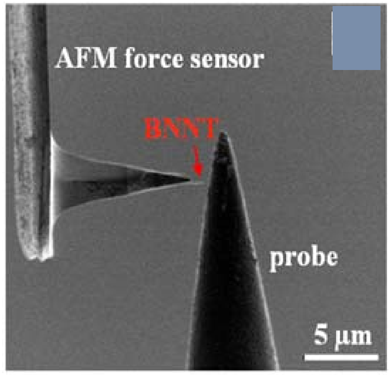


SEM



Tensile Test



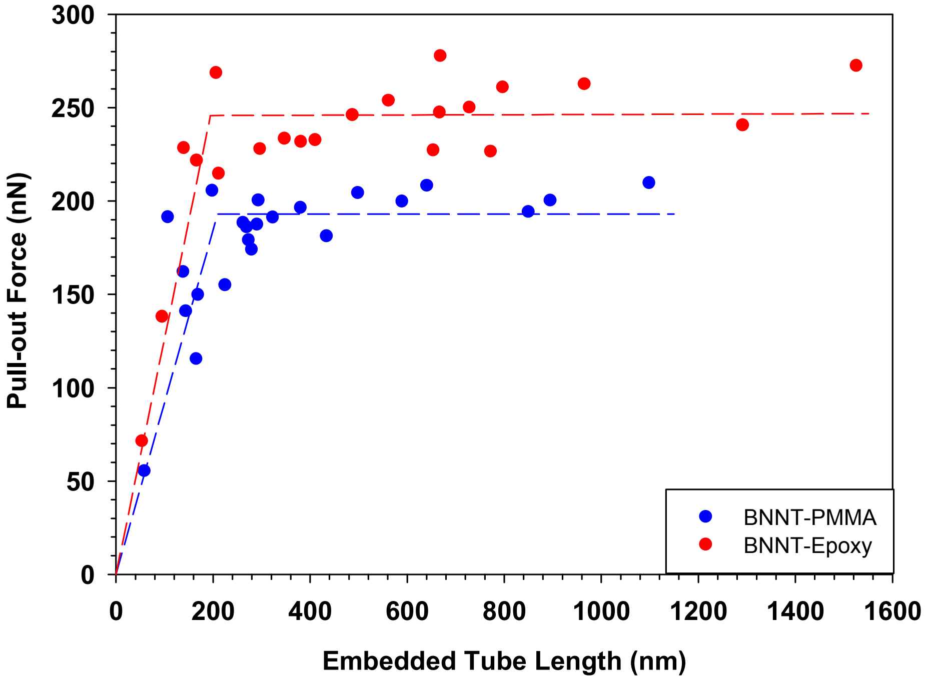


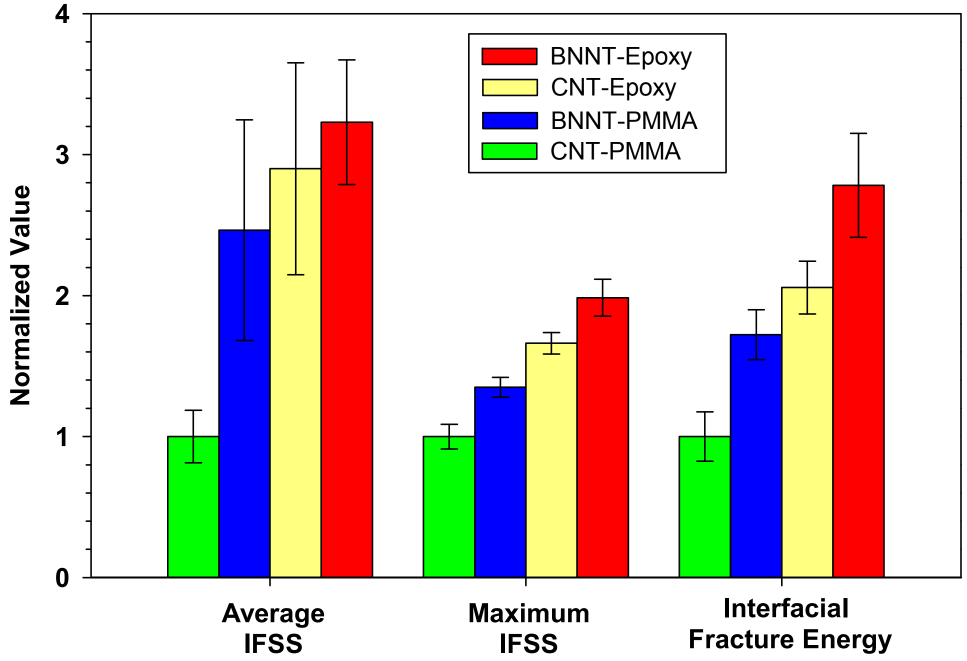
Small **9** 3345 (2013), Carbon **82** 214 (2015), *APL* **107** 253105 (2015)
Carbon **25** 93 (2017), *Carbon* **132** 548 (2018), *Nanotechnology* **30** 025706 (2019)

Credit: Prof Ke (SUNY Binghamton)

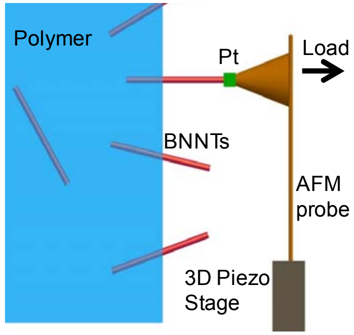
FEI Nanolab 600

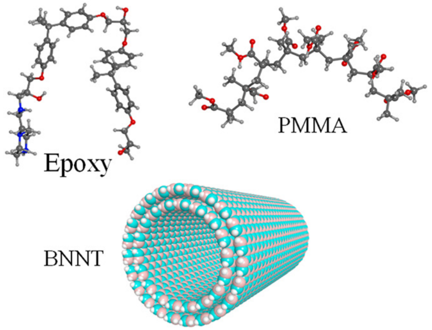
Interfacial Strength: *In-situ* Single Nanotube Pull-Out Test

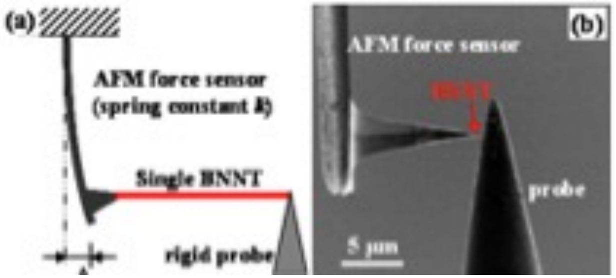




Interfacial strength of BNNT is superior to that of CNT







BNNT Tensile Test Results

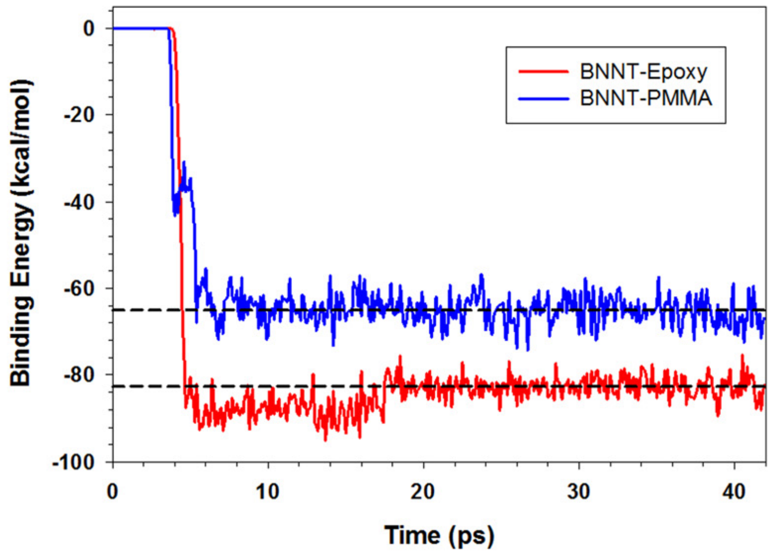
Diameter	Elastic modulus (GPa)	Breaking Strength (GPa)
D = 2.5 nm	760-960	14-38

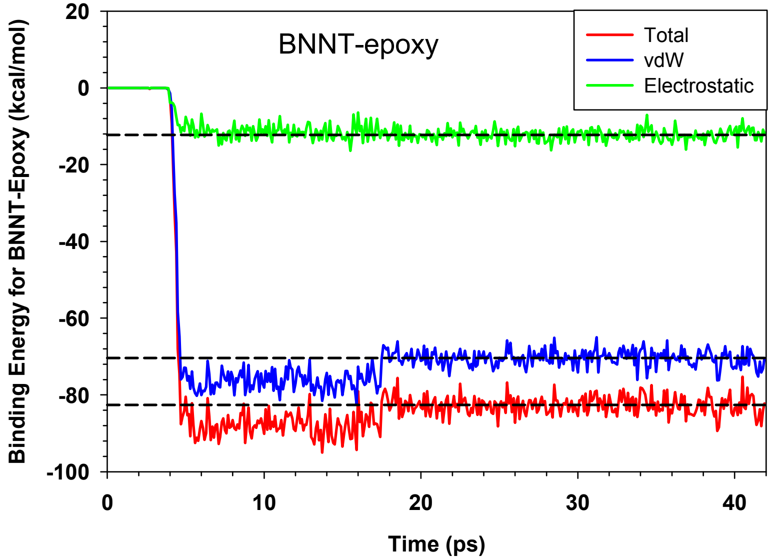
Small **9** 3345 (2013), Carbon **82** 214 (2015), *APL* **107** 253105 (2015)

Credit: Prof Ke (SUNY Binghamton)

Interfacial Strength: *In-situ* Single Nanotube Pull-Out Test

Credit: Prof Ke (SUNY Binghamton)



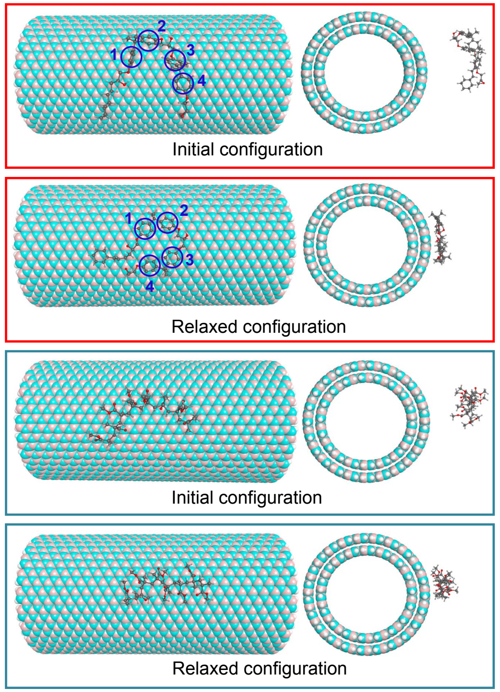


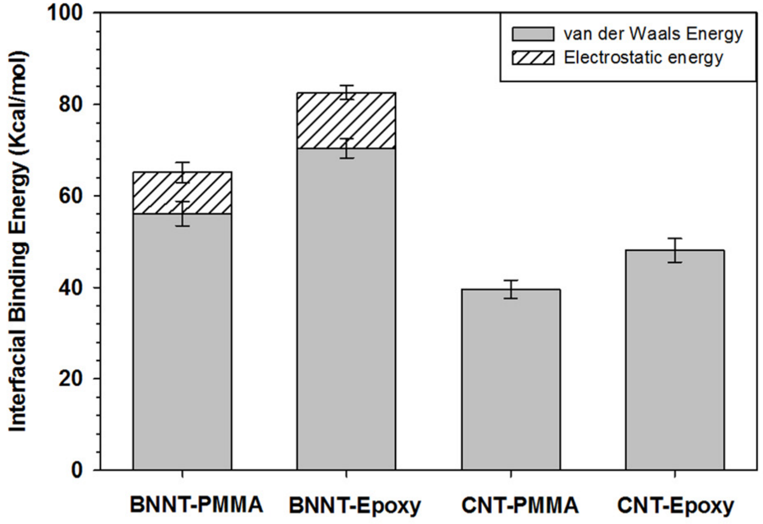
BNNT/Epoxy

BNNT/Epoxy

BNNT/PMMA

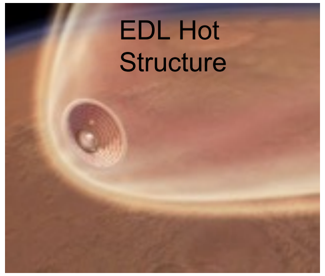
BNNT/PMMA

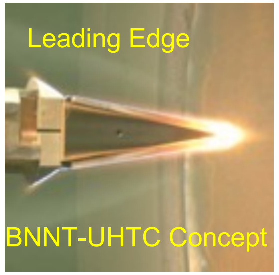


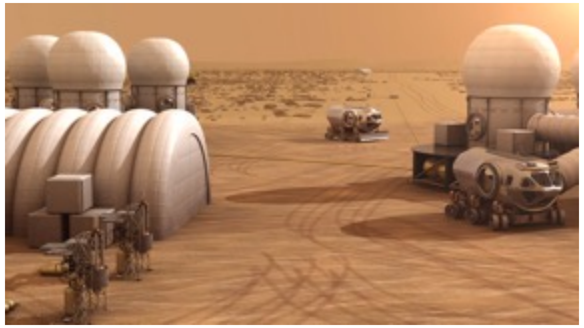


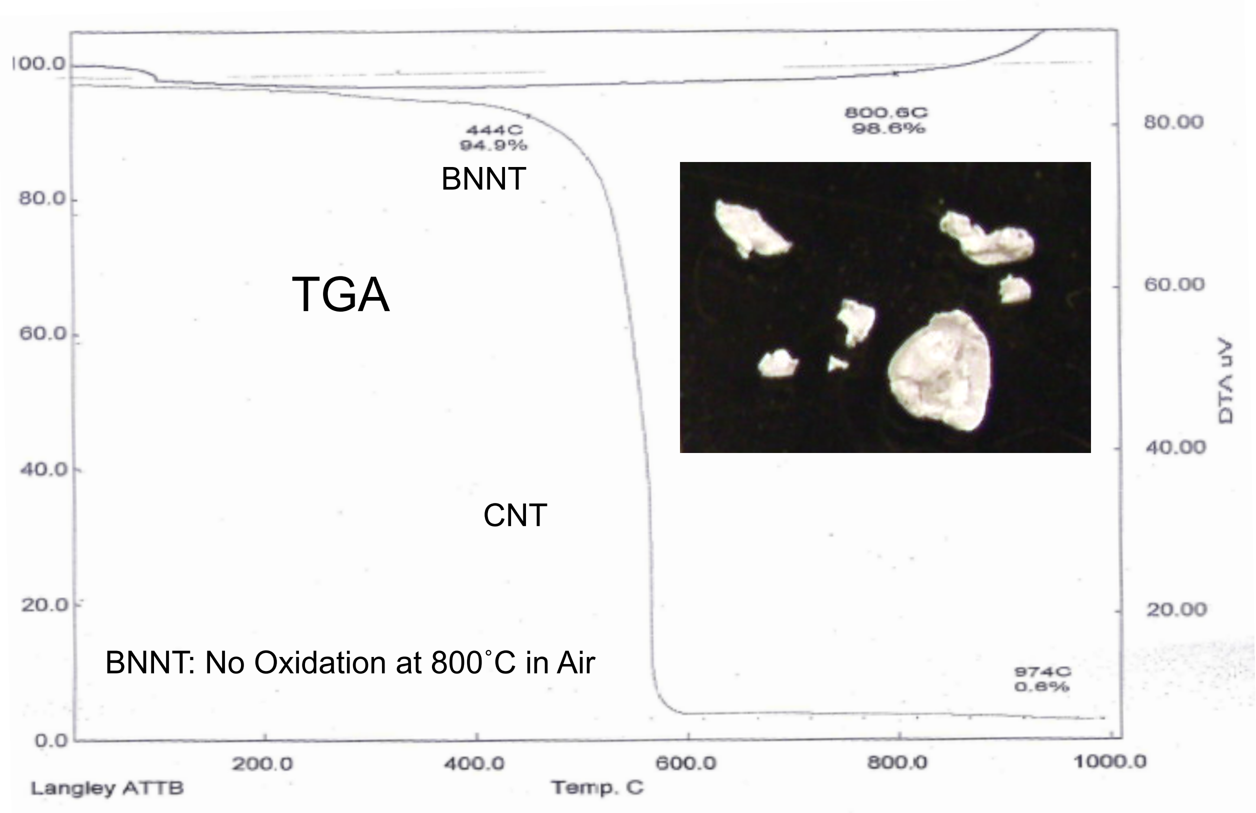
Small **9** 3345 (2013), Carbon **82** 214 (2015), *APL* **107** 253105 (2015)

Thermal Properties of BNNT









All images credit: NASA

Nanotechnology, **20** 505604 (2009)

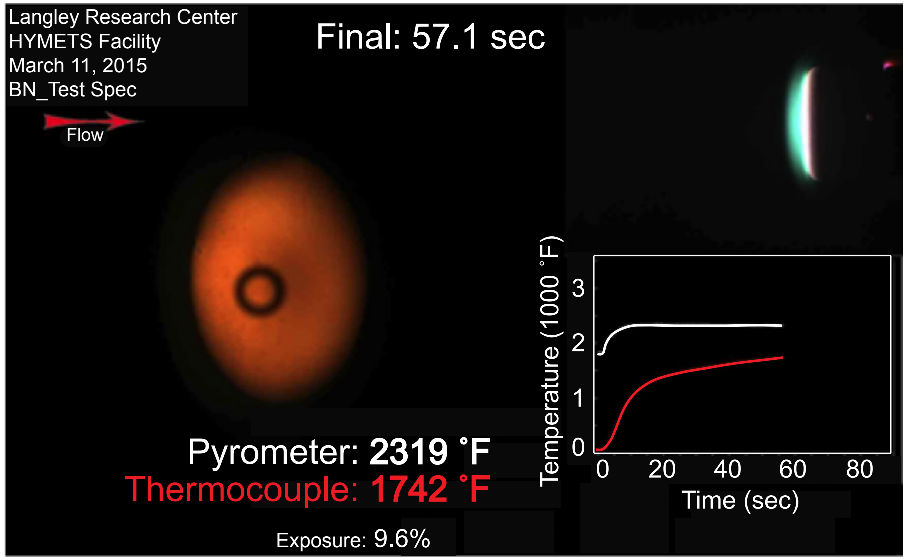
Hypersonic Materials Experiment Test System (HyMETS)

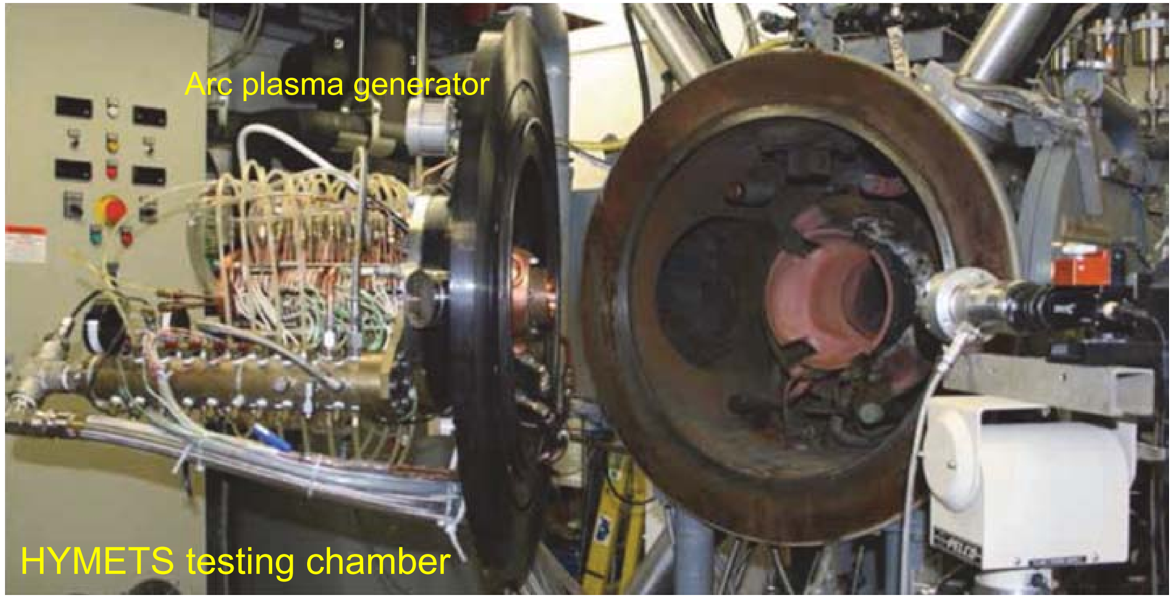
LaRC HYMETS Test Conditions

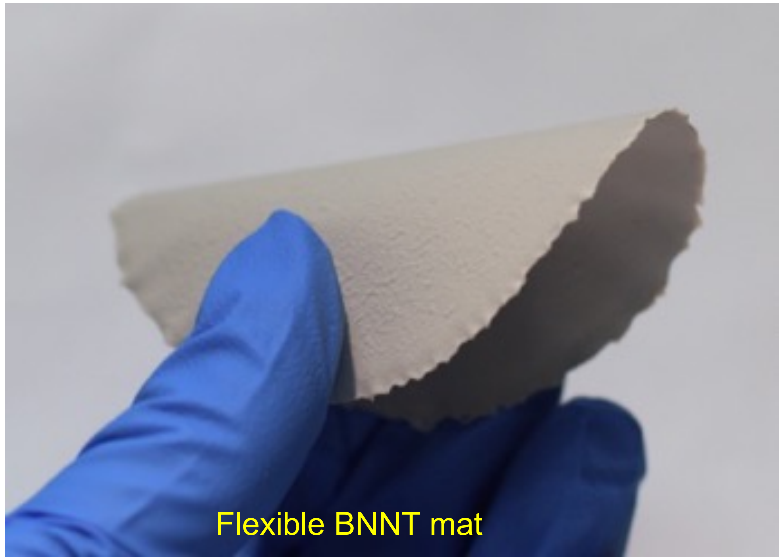
- Specimen Surface Temperature (°C): 1260
- Specimen Stagnation Pressure (atm): 0.013-0.079
- Free Stream Mach Number: 5.0
- Free Stream Enthalpy (kJ/kg): 5350-26749

HYMETS TEST for BNNT Mats

- Heat flux: Set at **50 W/cm²** (**2nd Gen Mars EDL**)
- Duration: 1 min - 5 min
- Atmosphere: Air (with 5% Ar)
- Cooled under Vacuum







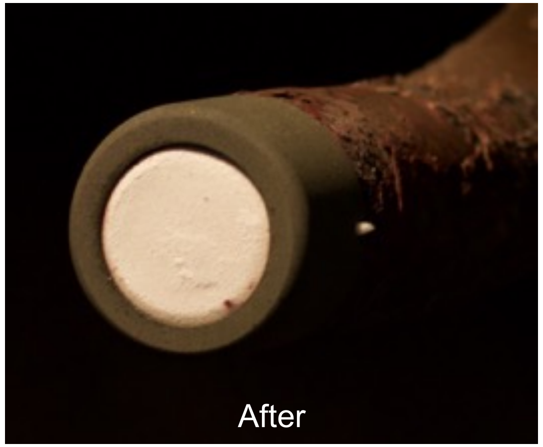
All images credit: NASA

Collaborators: Scott Splinter, Jeff Gragg, Kamran Daryabeigi (AIAA, 2011)

Hypersonic Materials Experiment Test System (HYMETS)

<u>Sample: BNNT Mat</u> <u>(as grown, nonwoven)</u>

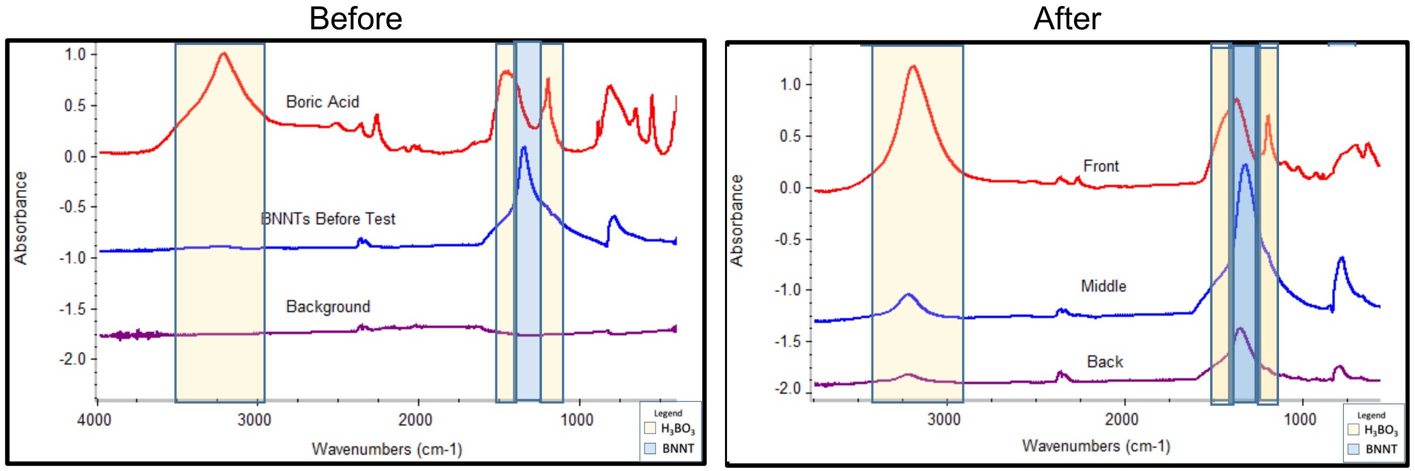
- Fabricated by a vacuum filtration process
- Diameter: 25 mm, Thickness: 2 mm, Density: ~ 0.3 g/cm^3

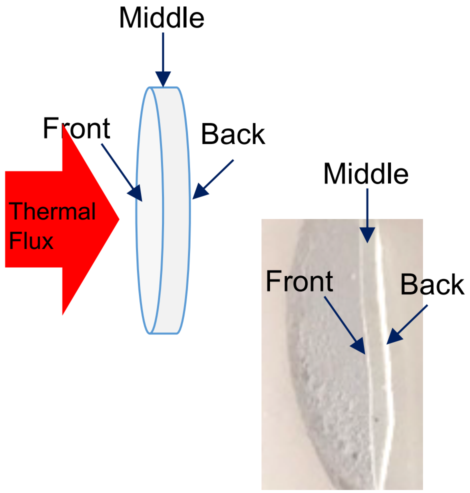


<u>HYMETS Test Conditions</u>

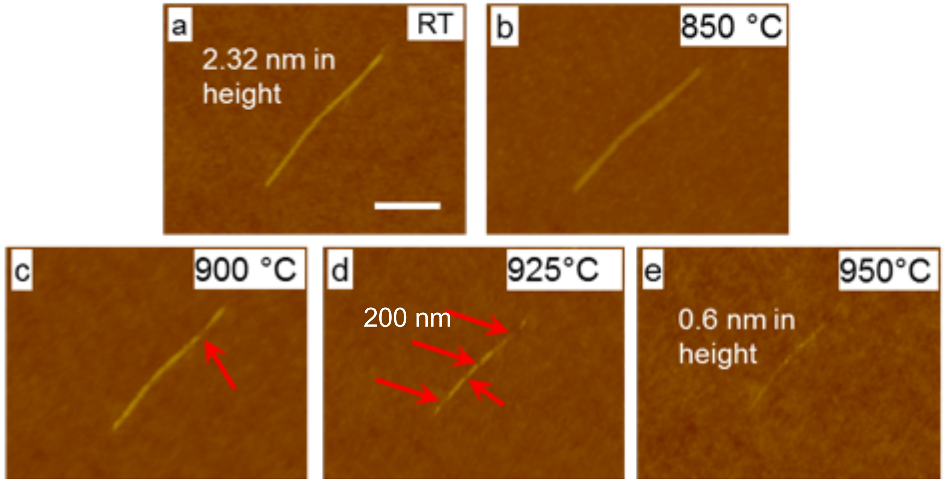
- Test duration: 1 min
- Surface temperature: 2400 ^oF (1315 ^oC)

<u>FT-IR Analysis of BNNT mat</u>

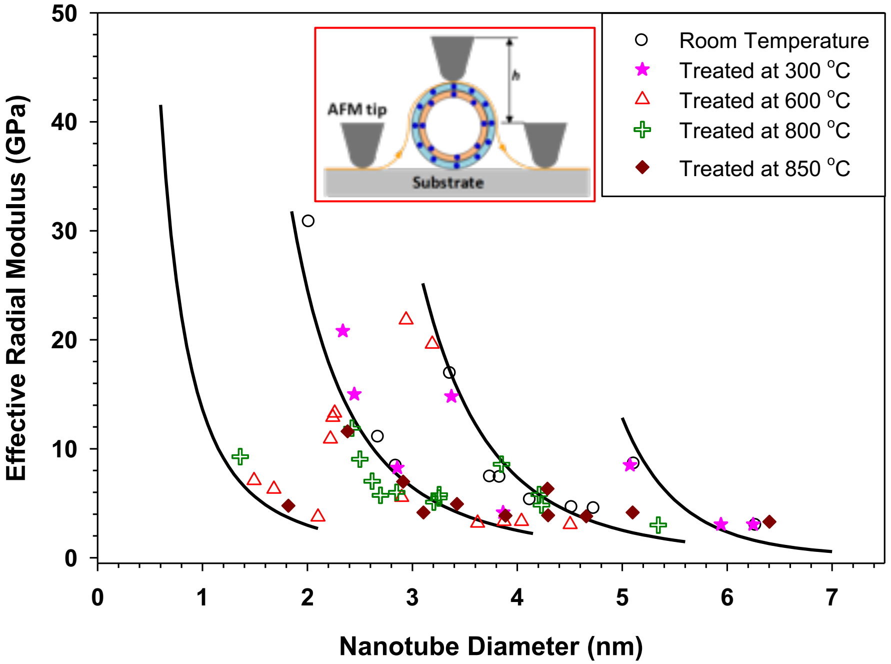




Superior Structural and Mechanical Properties of BNNTs in High Temperature Environments

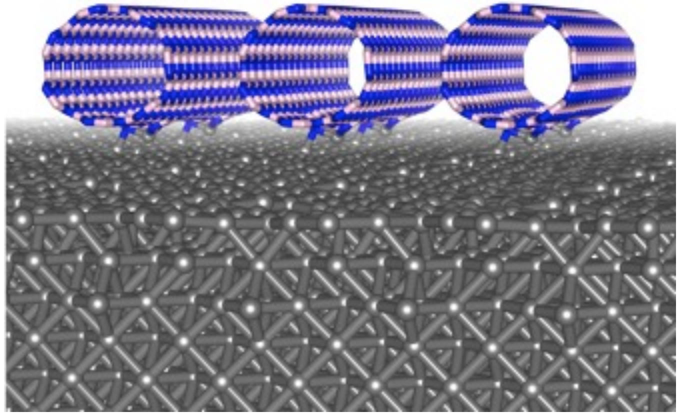


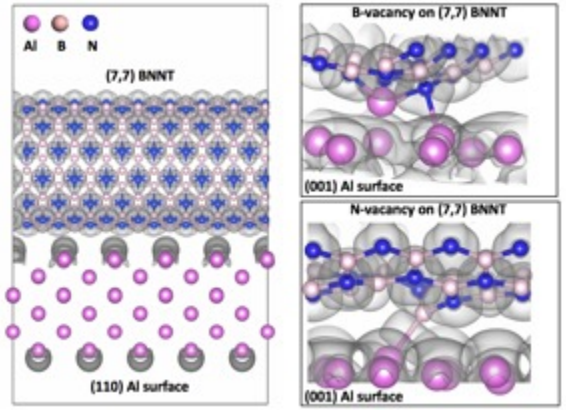
AFM studies show that individual BNNTs can survive at up to 850 ˚C in air and captures the sign of their structural degradation at 900 ˚C and above. (the red arrows mark the positions of the oxidation-induced tube broken sites).



AFM-based nanomechanical compression tests (illustrated in inset drawing) show that the mechanical properties of individual BNNTs remain intact after thermally baked at up to 850 ˚C in air.

BNNT Metal Matrix Composite (MMC)
BNNT Ceramic Matrix Composite (CMC)

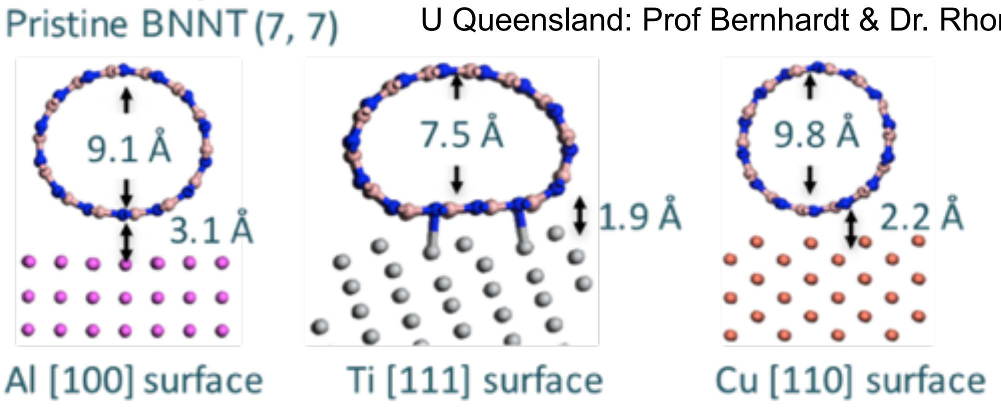


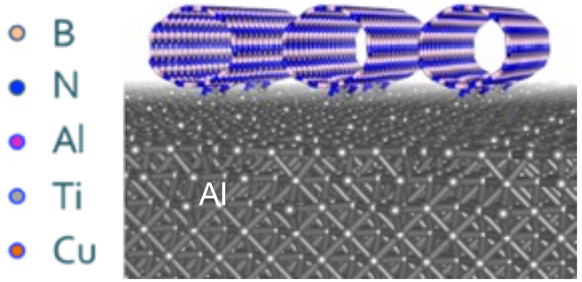


J. Phys. Chem. C **120** 3509 (2016)
J. Phys. Chem. C **122** 15266 (2018)

BNNT Metal Matrix Composite (BNNT-MMC)

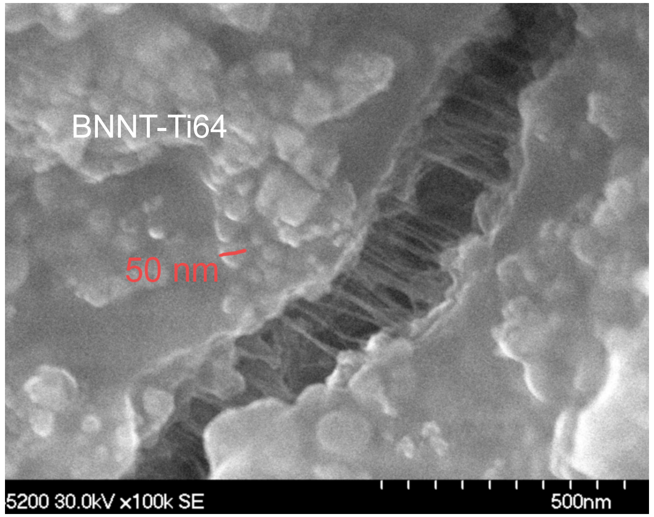
U Queensland: Prof Bernhardt & Dr. Rhomann (AFOSR/AOARD) Binghamton U: Prof Ke group (AFOSR)

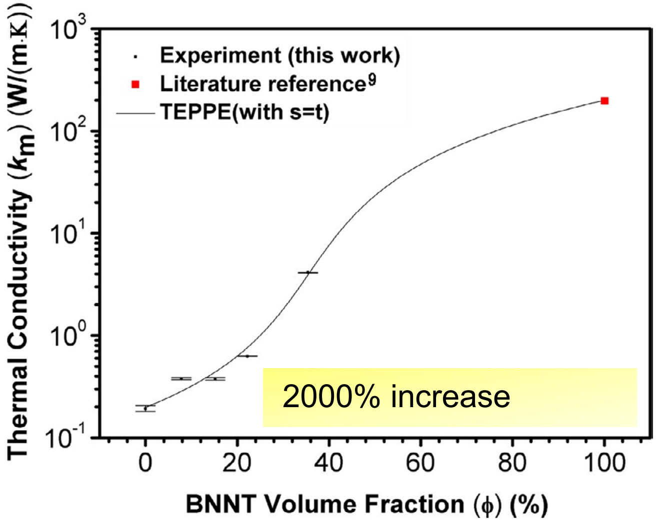


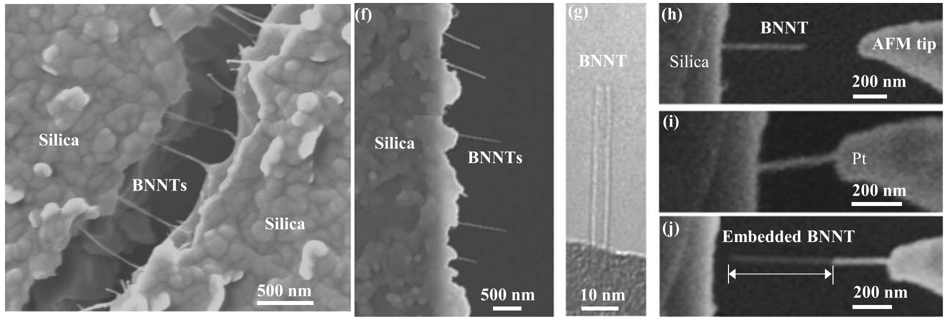


Interfacial strengths of BNNT are superior to that of CNT in **PMC**, **CMC**, and **MMC**.

Binding Energies**	Al[100] Surface	Ti[111] Surface	Cu[110] Surface
Pristine	-0.41	-1.77	-0.95
N-vacancy	-0.69	-2.00	-1.23
B-vacancy	-1.26	-3.30	n/a
C sub N	-0.64	-2.17	-1.26
C sub B	-0.51	-1.41	-1.00





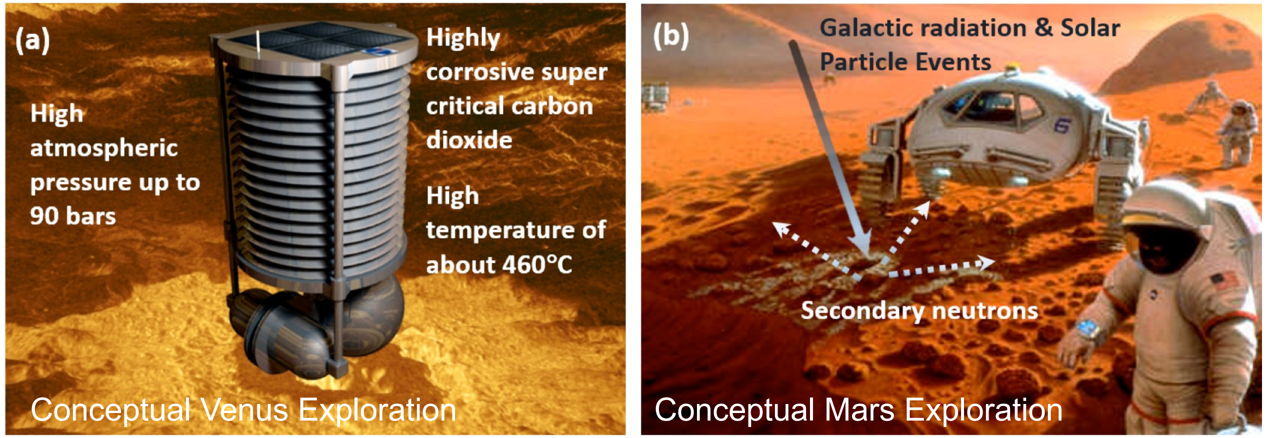


J. Phys. Chem. C **120** 3509 (2016)
J. Phys. Chem. C **122** 15266 (2018)
Nanotechnology, **30** 25706 (2019) BNNT-ceramic interfacial strength

J. Am. Cer. Soc. **109** 7584 (2019)

Multifunctional BNNT Polymer Composites

- Electroactive Properties
- Radiation Shielding Properties

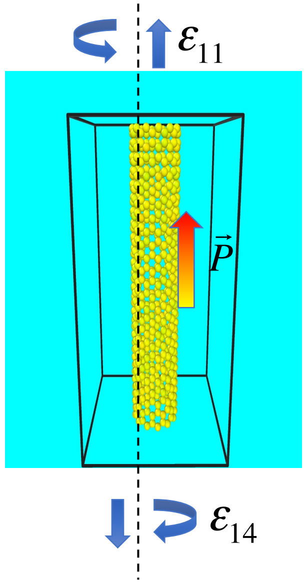


All images credit: NASA

MRS Bulletin **40** 836 (2015)
Comp. Mater. Sci., **95** 362 (2014)
ACS Nano **9** 11942 (2015)

Results: Piezoelectricity under Deformation

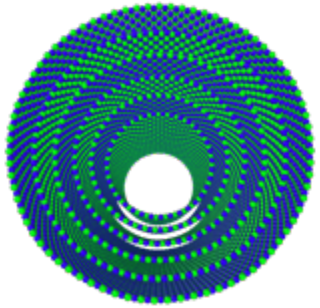
The Molecular Dynamics (MD) model is successful in representing the piezoelectric properties of BNNTs

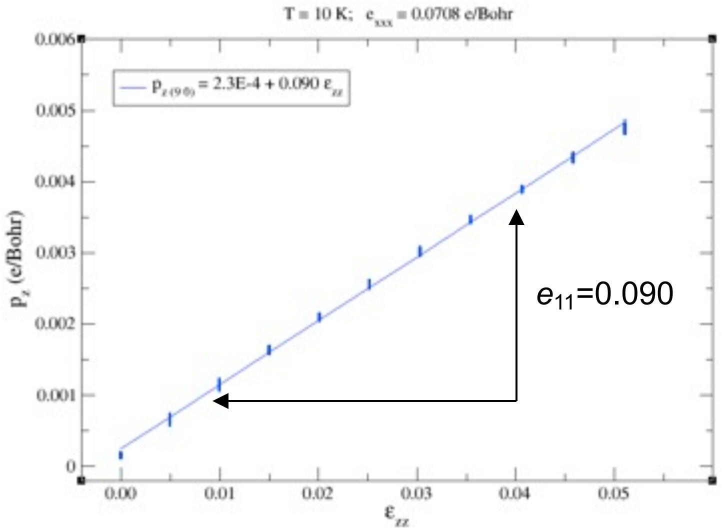


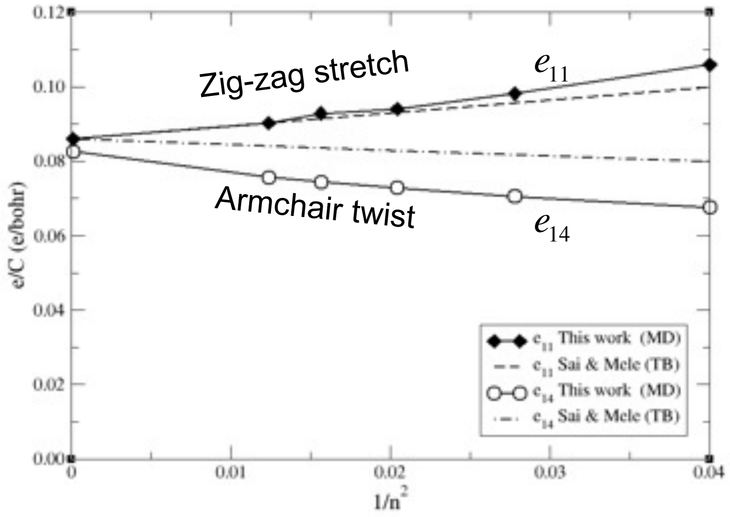
$p_z(stretch) = e_{11}\varepsilon_s$

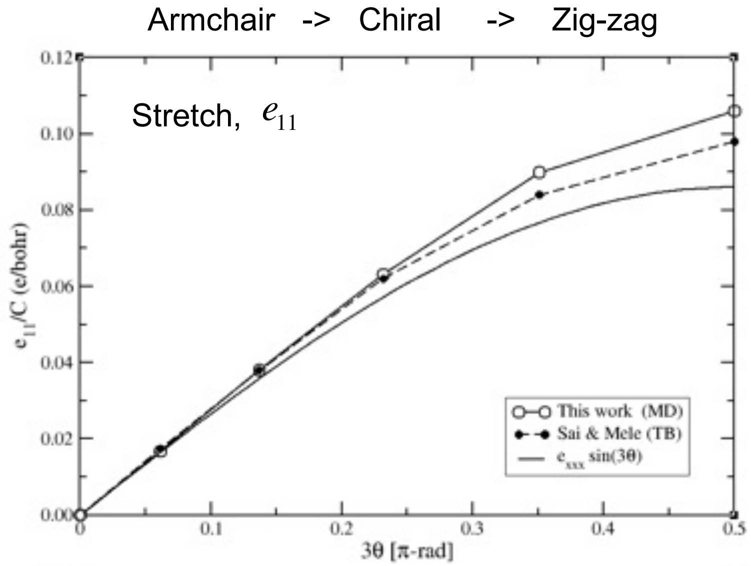
$p_z(twist) = e_{14}\varepsilon_t$

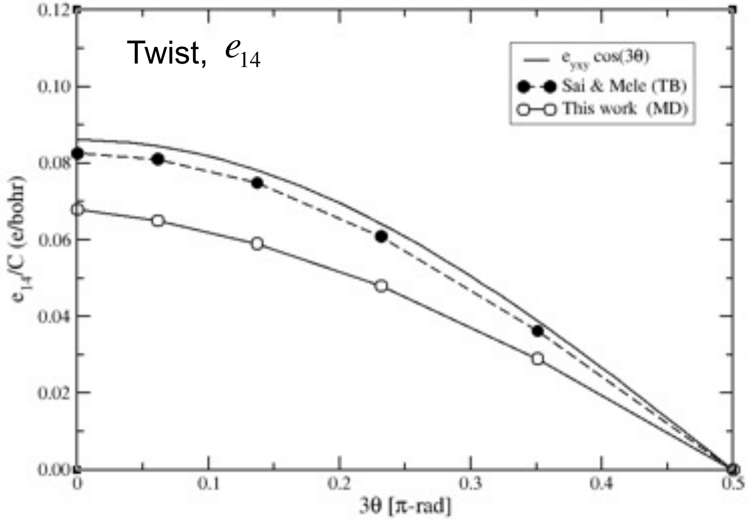
MWBNNT







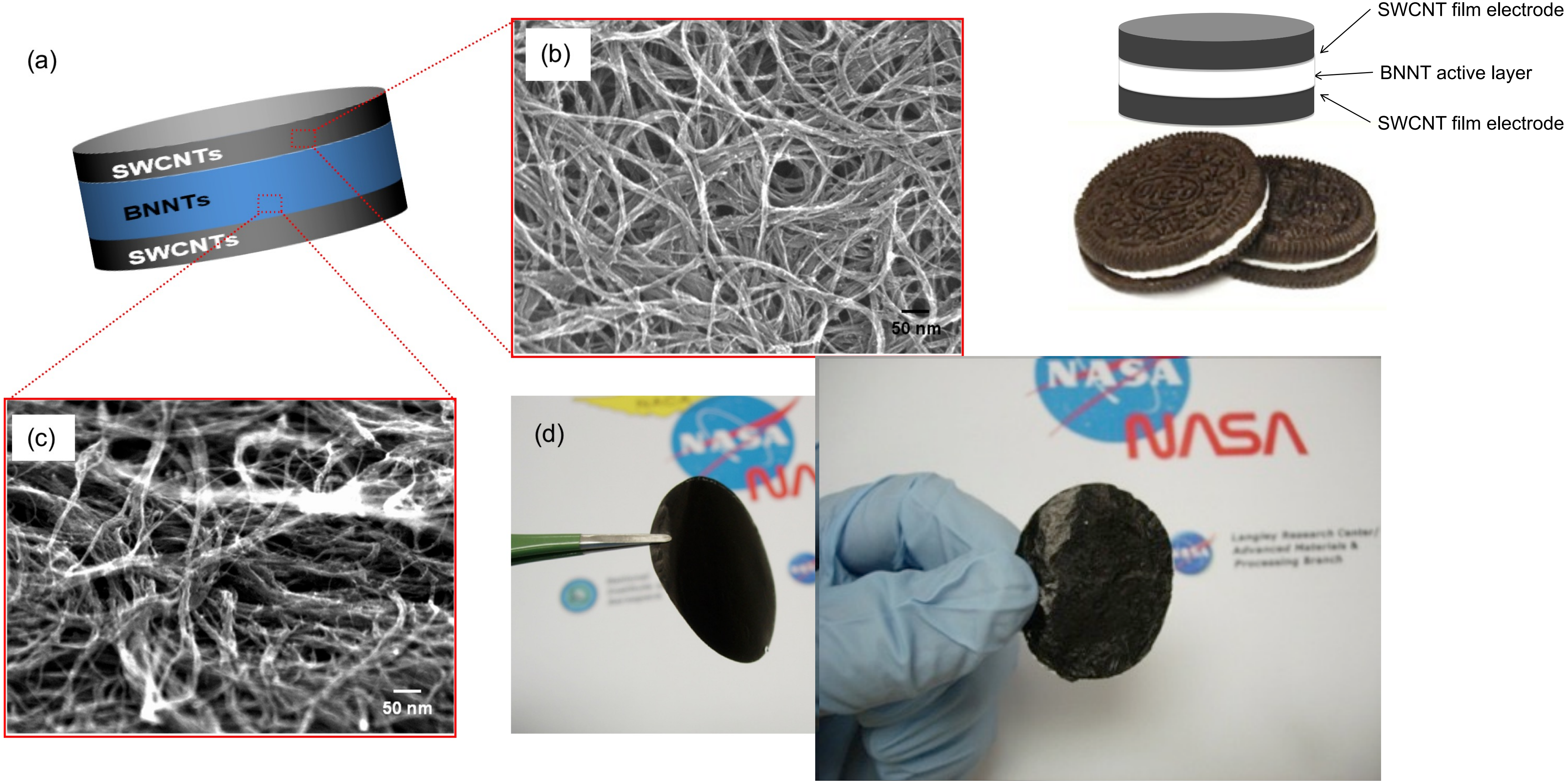




Comp. Mater. Sci., **135** 29 (2017)

Comp. Mater. Sci., **95** 362 (2014)

Langley All-Nanotubes Actuator/Sensor (LaRC-ANAS) Film

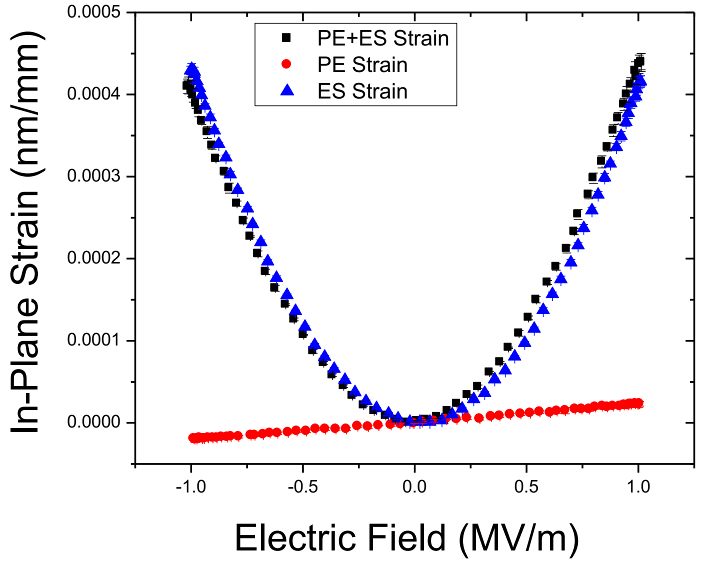


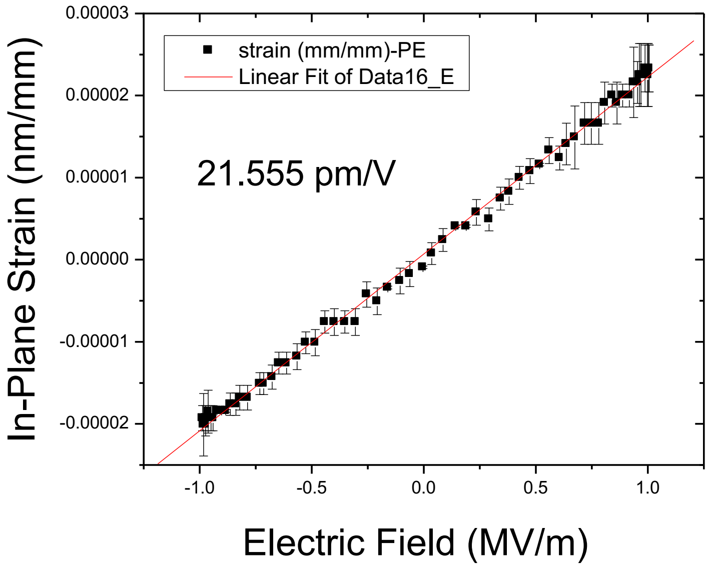
Goal: Flexible, transparent, large actuation, high sensitivity, mechanically durable

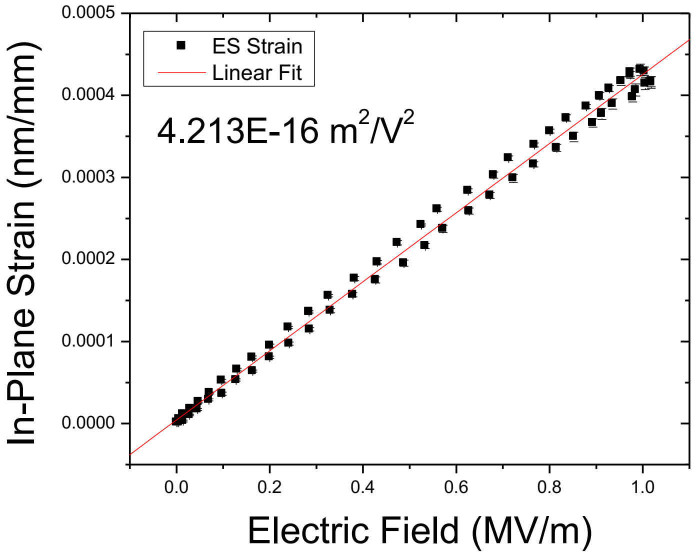
All images credit: NASA

ACS Nano **9** 11942 (2015)

All-Nanotubes Actuator/Sensor Film: In-Plane Strain







Field induced strain (e_{33})

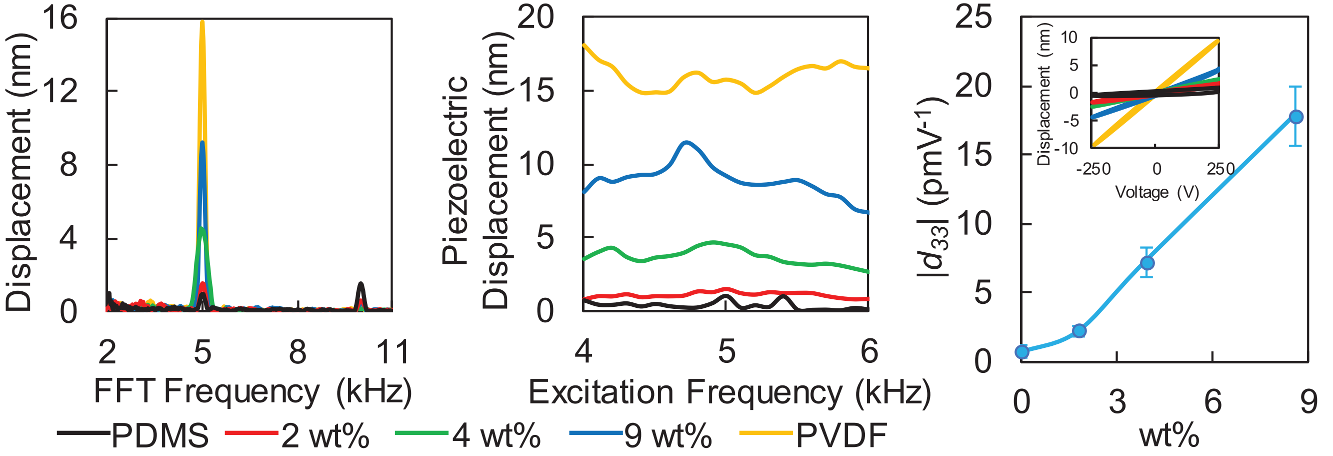
$$e_{33} = d_{33} \cdot \boldsymbol{E} + M_{33} \cdot \boldsymbol{E}^2 + \ldots$$

d_{33}: piezoelectric coefficient
M_{33}: electrostrictive coefficient
E: applied electric field

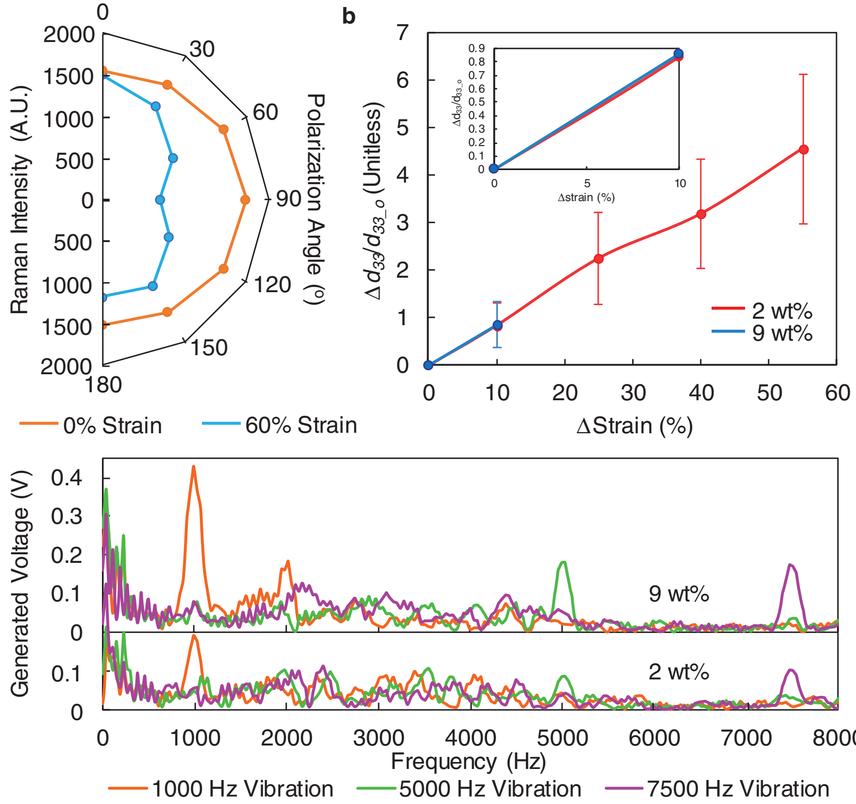
ACS Nano **9** 11942 (2015)

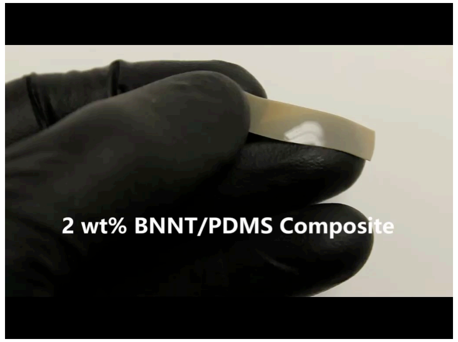
Multifunctional Properties of BNNT/PDMS (Poly(dimethylsiloxane))

Piezoelectric Properties of BNNT/PDMS

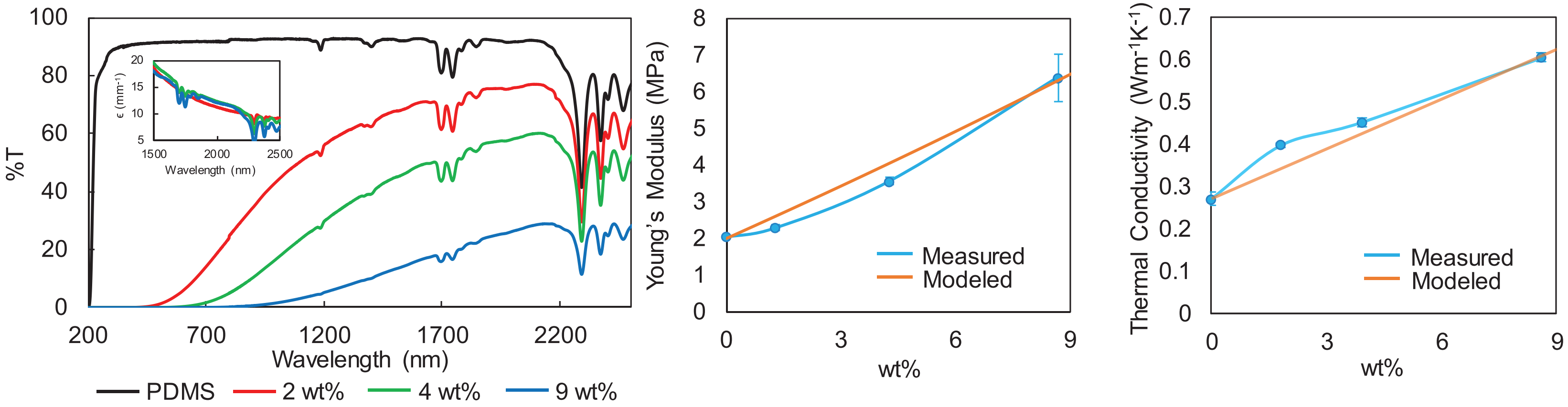


Alignment Effect & Vibration Sensing of BNNT/PDMS





Optical, Mechanical, and Thermal Properties of BNNT/PDMS



Credit: Dr. Peter Snapp (NASA GSFC) and Professor SungWoo Nam

Advanced Materials, **32**, 2004607(2020)

Radiation Shielding Properties

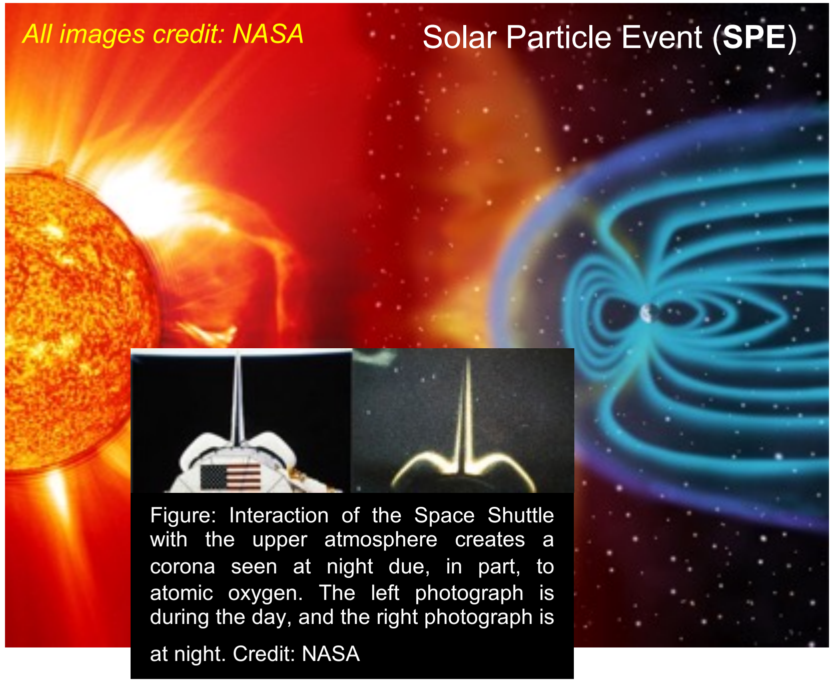
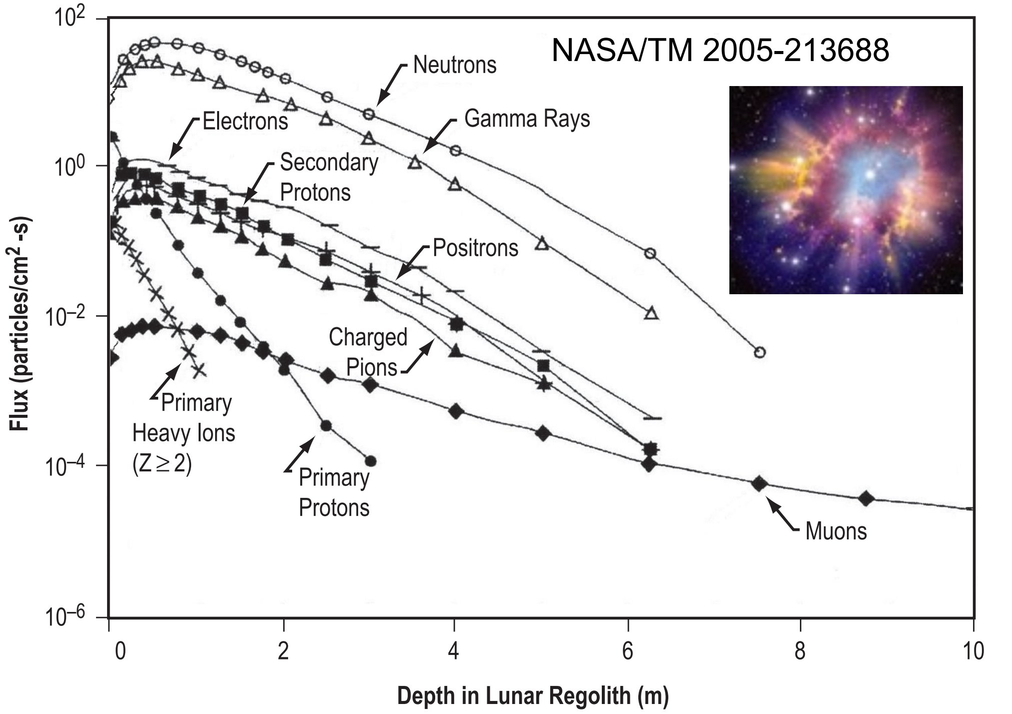


Figure: Interaction of the Space Shuttle with the upper atmosphere creates a corona seen at night due, in part, to atomic oxygen. The left photograph is during the day, and the right photograph is at night. Credit: NASA

Science **340** 1080 (2013)

Galactic Cosmic Ray (**GCR**) and produced Secondaries in lunar regolith



Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory

C. Zeitlin,[1*] D. M. Hassler,[1] F. A. Cucinotta,[2] B. Ehresmann,[1] R. F. Wimmer-Schweingruber,[3] D. E. Brinza,[4] S. Kang,[4] G. Weigle,[5] S. Böttcher,[3] E. Böhm,[3] S. Burmeister,[3] J. Guo,[2] J. Köhler,[3] C. Martin,[3] A. Posner,[6] S. Rafkin,[1] G. Reitz[7]

The Mars Science Laboratory spacecraft, containing the Curiosity rover, was launched to Mars on 26 November 2011, and for most of the 253-day, 560-million-kilometer cruise to Mars, the Radiation Assessment Detector made detailed measurements of the energetic particle radiation environment inside the spacecraft. These data provide insights into the radiation hazards that would be associated with a human mission to Mars. We report measurements of the radiation dose, dose equivalent, and linear energy transfer spectra. The dose equivalent for even the shortest round-trip with current propulsion systems and comparable shielding is found to be 0.66 ± 0.12 sievert.

Spacecraft data nails down radiation risk for humans going to Mars

Nature News, May 30, 2013, Ron Cowan
Interviewed Sheila Thibeault at NASA Langley about the study published in *Science*
Mars Science Laboratory (MSL) during its cruise to Mars between 6 December 2011 and 14 July 2012 (253 days)

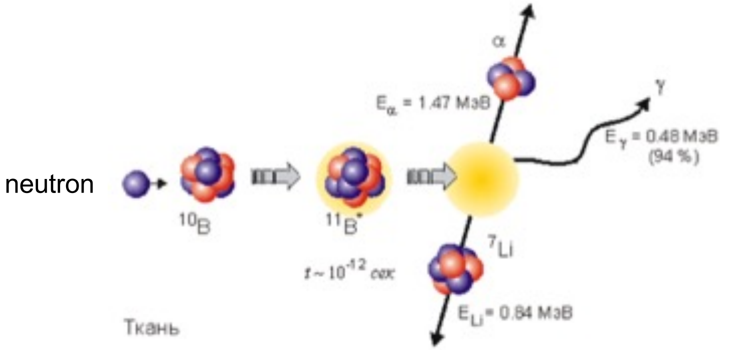
Mars Round Trip Dose Equivalent is around 0.66 Sievert

MRS Bulletin **40** 836 (2015)

Radiation Tests: LaRC Radiation Exposure Test Facility

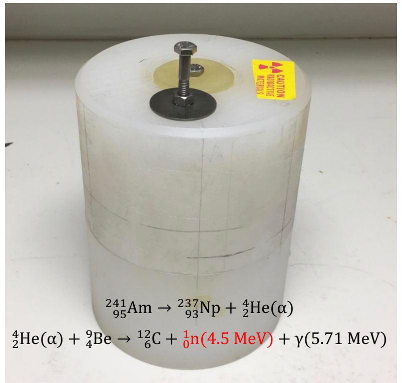
Neutron Source

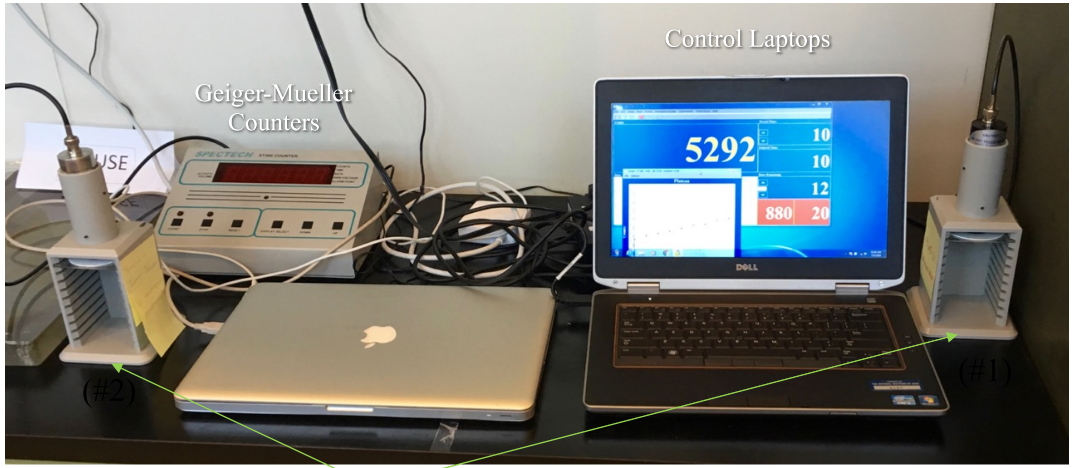
- Radioactive Source: Am/Be (1 Curie) source produces fast neutron (4.5 MeV) and thermal neutrons (<0.5 eV) by borated PE cylinder (44 mm thick)
- Sample: 2"x 2"
- Detection Foil: 1.25" Indium Foil (0.5mm, 19 barns), $^{115}In(n, \gamma)^{116}In$



http://www.inp.nsk.su/bnct/introduction/introduction.en.shtml

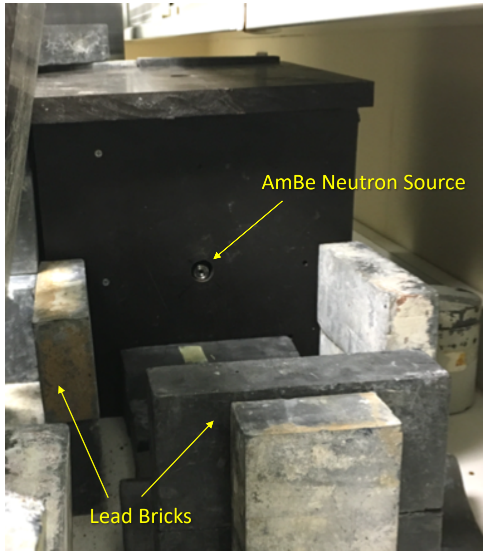
Low Dose Rate
(45 mrem/hr, dose equivalent rate)

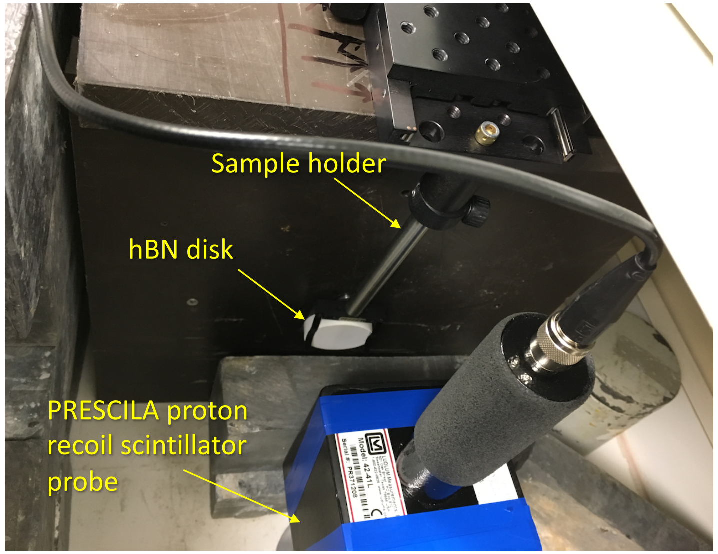




Geiger-Mueller Detectors

High Dose Rate
(800 mrem/hr, dose equivalent rate)

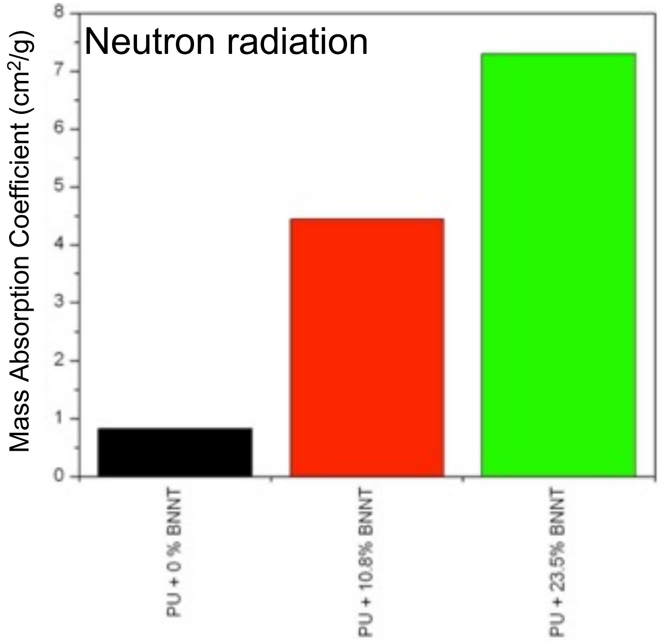




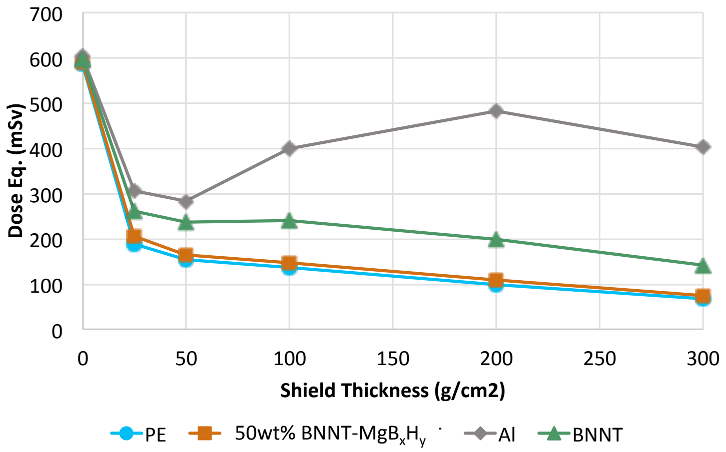
Dose Equivalent Rate Measurement

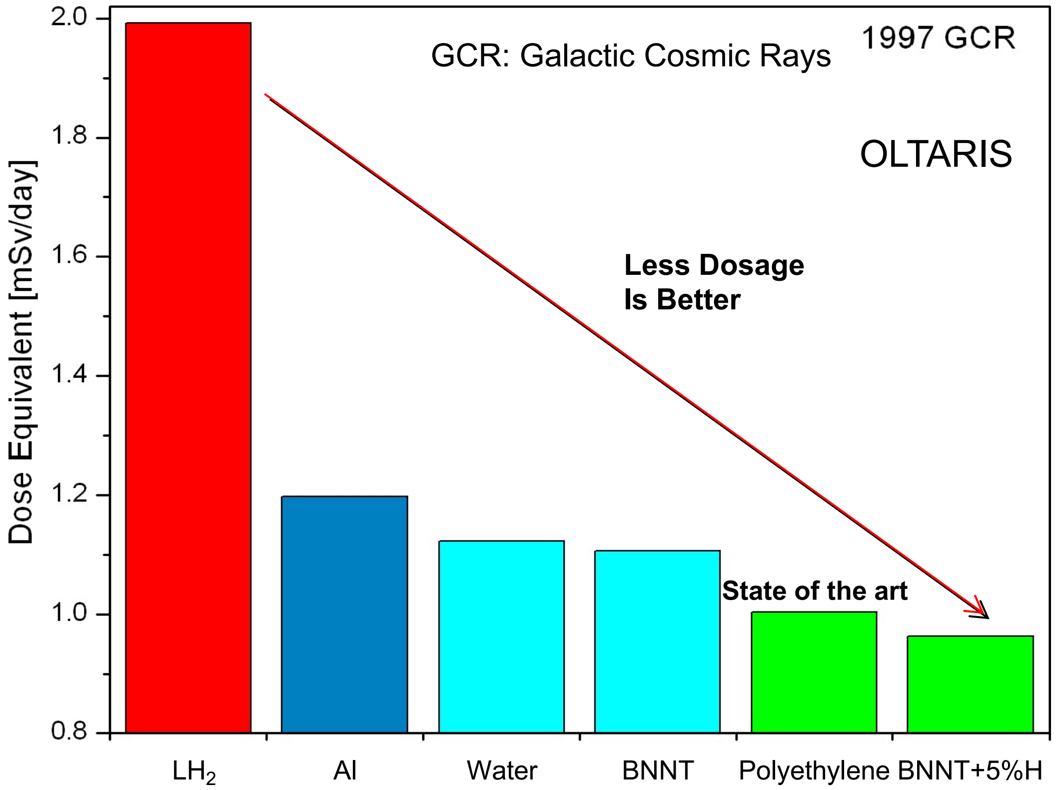
- Neutron survey meter: Ludlum Portable Survey, Model 2363
- Probe: PRESCILA proton recoil scintillator probe (Model 42-41L)
- Detection range: 0.1 mrem/hr to 1 rem/hr

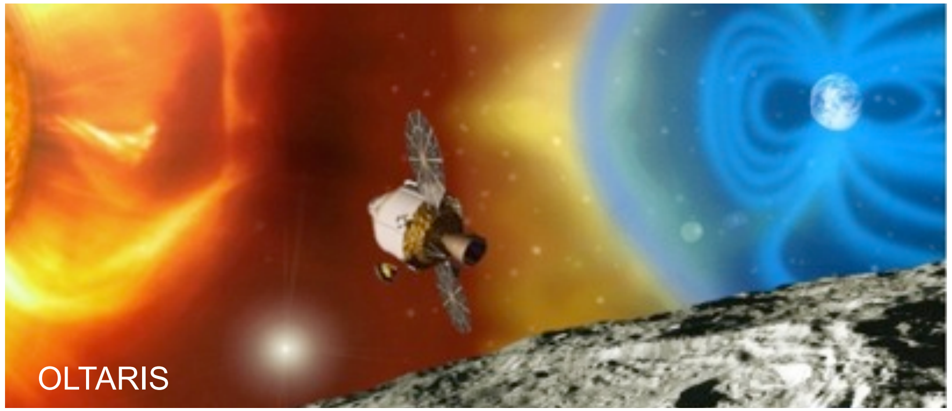
Radiation Shielding Effectiveness of BNNT Composites



BON-14 GCR Model in Free Space with 1977 Solar Min. incident on Vehicles with varying thicknesses





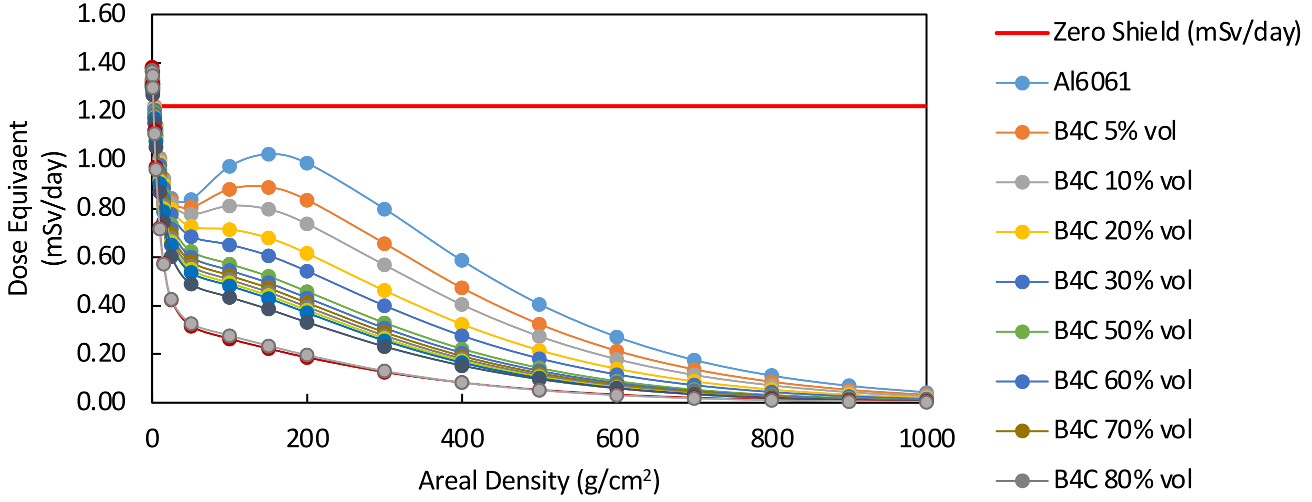


Credit: Victoria Arias (NIFS), NASA TM (2021)

http://www.nasa.gov/pdf/716082main_ Thibeault_2011_PhI_Radiation_Protection.pdf (NASA NAIC Phase I Report)

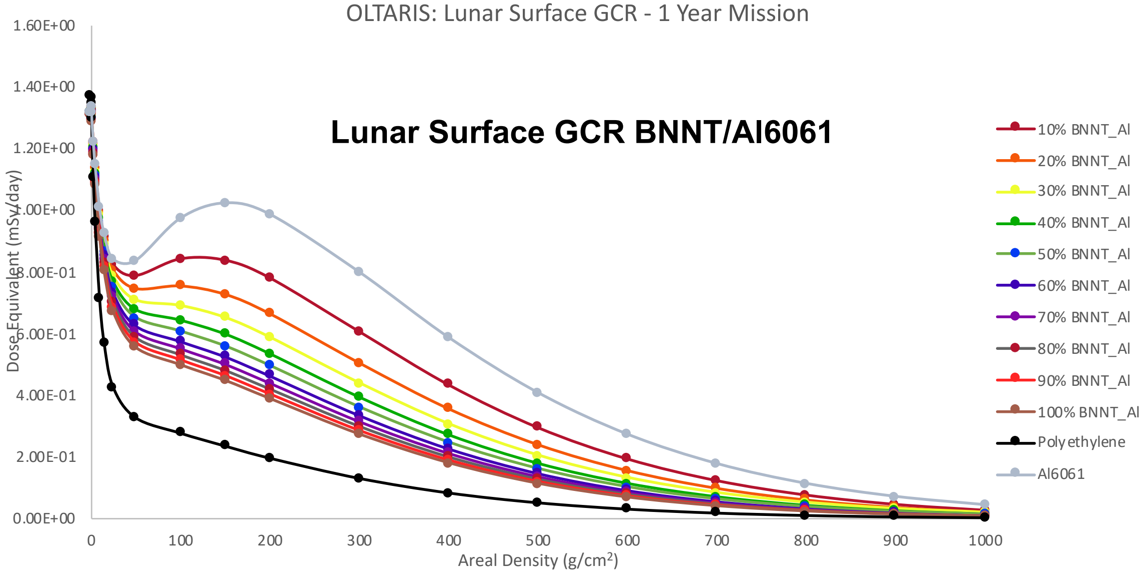
OLTARIS: GCR Lunar and Mars Surface Environment

BON-14 GCR Model on Lunar Surface with 1977 Solar Min. Incident on Vehicles with varying thickness: B_4C/Al6061



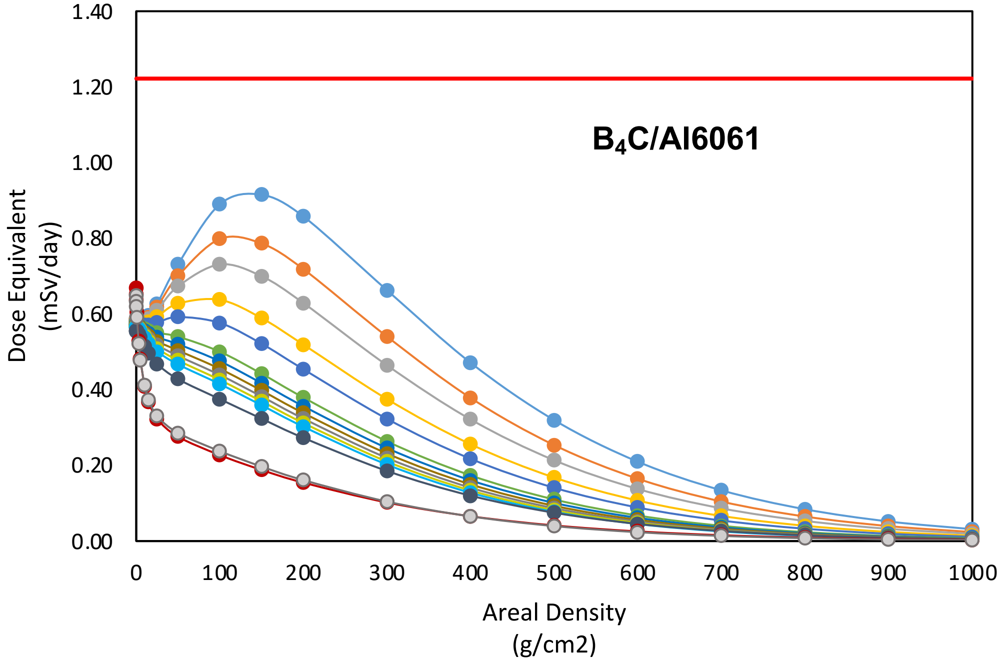
Parameters
Environment Selection: GCR, Lunar Surface
Mission Definition: Select historical Solar Min/Max
Historical Min/Max: August 1972 (King)
Mission Duration Days: 365

OLTARIS: Lunar Surface GCR - 1 Year Mission



Parameters
Environment Selection: GCR, Mars Surface
Mission Definition: Select historical Solar Min/Max
Historical Min/Max: August 1972 (King)
Mission Duration Days: 365
Mars Surface Parameters: MarsGRAM Atmosphere
Elevation: **0.0 km**

BON-14 GCR Model on Mars Surface with 1977 Solar Min. Incident on Vehicles with varying thickness



Credit: Calista Lum (NIFS, UC Merced), John Lyons (NIFS, UK)

Summary

- High Temperature-Pressure BNNT synthesis method was introduced.
- BNNT dispersion was successfully achieved by thermodynamic approach using Hansen solubility parameters for single and co-solvent systems.
- Interfacial shear strength and fracture energy of BNNT with polymer, metal, and ceramic matrices were superior to those of CNT.
- BNNT exhibited excellent thermal stability under a simulated planetary entry environment along with flame resistance and retardation properties
- BNNT and BNNT polymer composites exhibited excellent piezoelectricity as well as electrostrictive behavior even without poling.
- BNNT exhibited excellent neutron radiation shielding effectiveness and hydrogen containing BNNT showed superb shielding effectiveness against GCR and SPE.

Acknowledgements

NASA Langley Research Center

Catharine Fay, Samuel Hocker, Sharon Lowther, Godfrey Sauti, Wanda Gresham, Joseph Lee, Hoa Luong, Peter Gnoffo, Paul Danehy, Jennifer Inman, Steve Jones, Sheila Thibeault, Peter Lillehei, Kristopher Wise, Robert Bryant, Crystal Topping, Dennis Working, Sang Choi, Bob Moses, Kamran Daryabeigi, Jeffrey Gragg, Scott Splinter, TEAMS3 (Joel Alexa, Peter Messick, Harold Clay Claytor), Victoria Arias (NIFS)

National Institute of Aerospace

Sang-Hyon Chu, Vesselin Yamakov, Jin Ho Kang, Hyun Jung Kim, Luke Gibbons, Samantha Applin, Amanda Tiano

SUNY Binghamton

Meng Zheng, Xiaoming Chen, Changhong Ke, Howard Wang

Rice University

Mohammad Adnan, Daniel Marincel, Matteo Pasquali

Georgia Tech

Huibin Chang, Prabhakar Gulgunje, Jeffrey Luo, Satish Kumar

NASA C&I, B&P, GCD, IRAD, CIF, NIAC, ECI

NASA Education Programs

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https://intern.nasa.gov/

NASA Space Grant
https://www.nasa.gov/stem/spacegrant/about/index.html

NASA Pathways Program
https://www.nasa.gov/careers/pathways-program

NASA Space Technology Graduate Research Opportunities (NSTGRO)
https://www.nasa.gov/directorates/spacetech/strg/nstgro

NASA Fellowship
https://www.nasa.gov/stem/fellowships-scholarships/index.html